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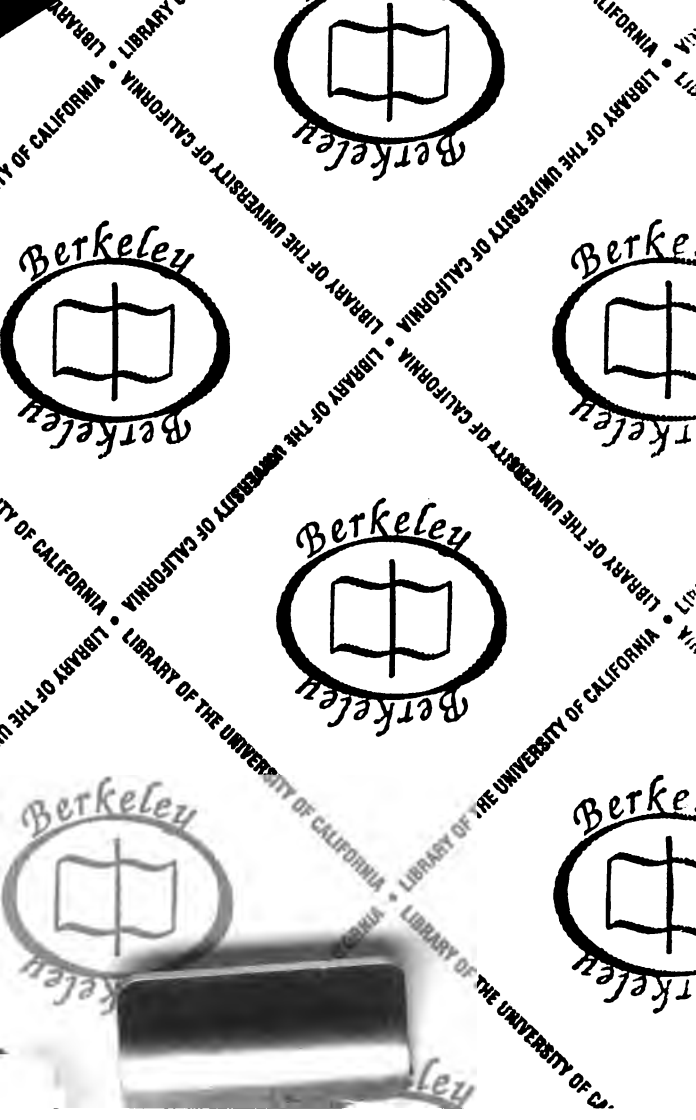
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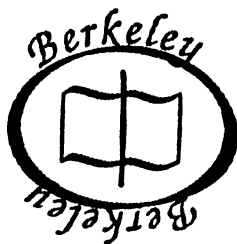
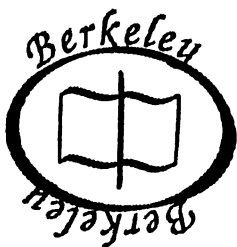
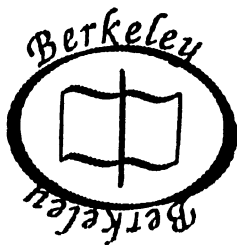
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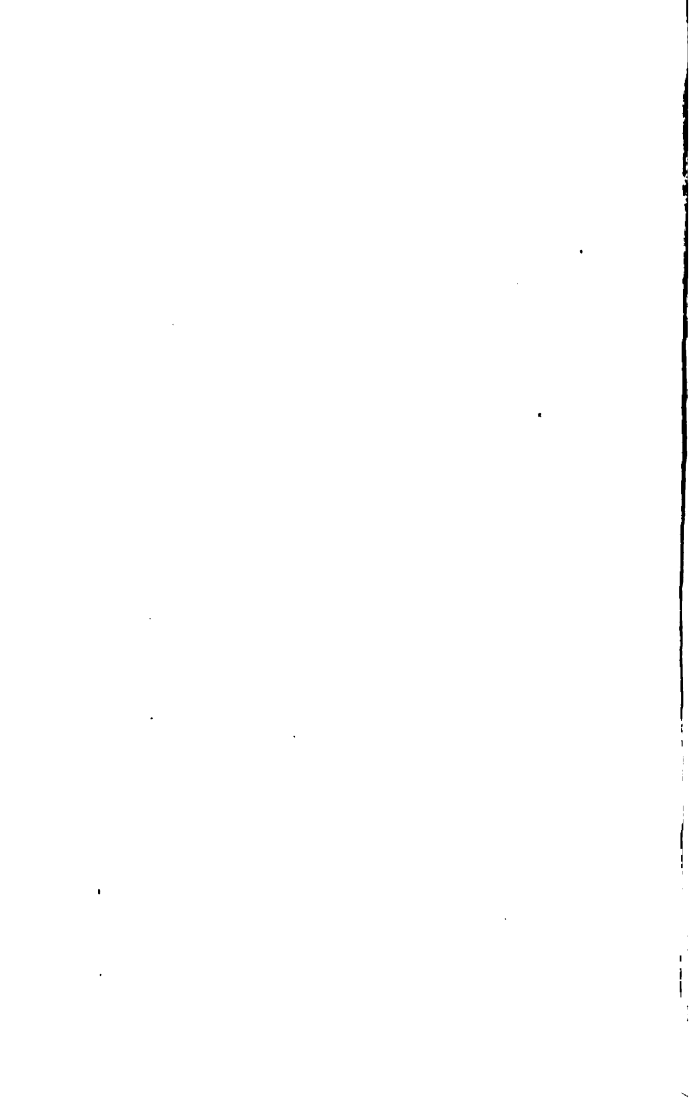


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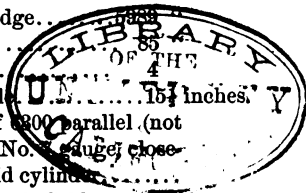
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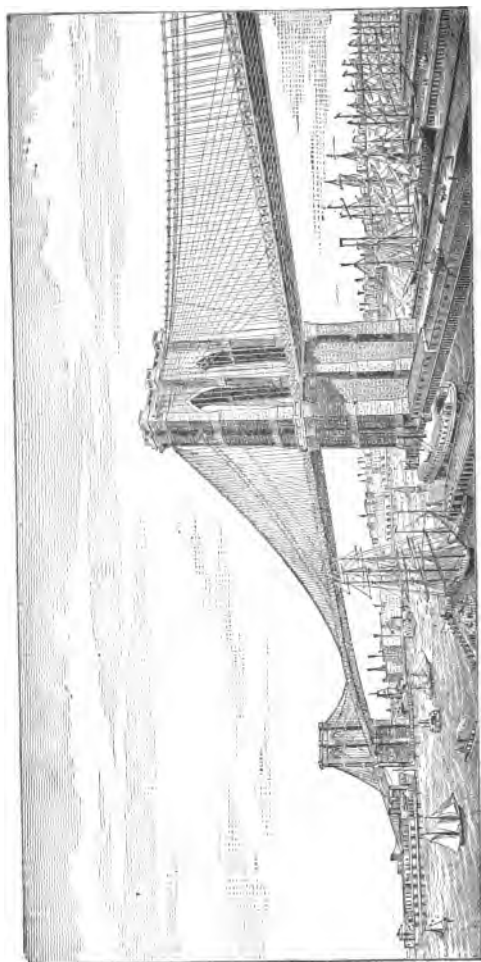
# EAST RIVER BRIDGE.

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|                                                                                                                             |                         |
|-----------------------------------------------------------------------------------------------------------------------------|-------------------------|
| Construction commenced.....                                                                                                 | Jan. 2, 1870.           |
| Length of River span.....                                                                                                   | 1595 feet 6 in.         |
| “ “ each Land span 930 ft.                                                                                                  | 1860 “                  |
| “ “ Brooklyn approach....                                                                                                   | 971 “                   |
| “ “ N. Y. approach.....                                                                                                     | 1562 “ 6 in.            |
| Total length of of Bridge.....                                                                                              | 5938 “                  |
| Width of Bridge.....                                                                                                        | 85 “                    |
| Number of Cables.....                                                                                                       | 4                       |
| Diameter of each Cable.....                                                                                                 | 15 1/4 inches.          |
| Each Cable consists of 300 parallel (not<br>twisted) steel wires No. 4 gauge, close-<br>ly wrapped to a solid cylinder..... |                         |
| Ultimate strength of each Cable....                                                                                         | 11,200 tons.            |
| Depth of Tower foundation below high<br>water, Brooklyn.....                                                                | 45 feet.                |
| Depth of Tower foundation below high<br>water, New York.....                                                                | 78 feet.                |
| Size of Towers at high water line,                                                                                          | 140x59 feet.            |
| Total height of towers above high wa-<br>ter .....                                                                          | 277 feet.               |
| Clear height of Bridge in centre of river<br>span above high water, at 50 degs F.                                           | 135 feet.               |
| Height of floor at towers above H. W.                                                                                       | 119 feet 3 inches.      |
| Grade of Roadway .....                                                                                                      | 3 1/4 feet in 100 feet. |
| Size of Anchorage at base.....                                                                                              | 129x119 feet.           |
| “ “ “ top... ..                                                                                                             | 117x104 feet.           |
| Weight of each Anchor-plate.....                                                                                            | 23 tons.                |
| Total cost of Bridge, exclusive land ac-<br>quisition.....                                                                  | \$9,000,000.            |







*Frank H. Maher.*  
**CABLE-MAKING**

FOR

**SUSPENSION BRIDGES,**

WITH SPECIAL REFERENCE TO THE

CABLES OF THE EAST RIVER BRIDGE.



REPRINTED FROM VAN NOSTRAND'S MAGAZINE.



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## PREFACE.

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THE following treatise was originally written for *Van Nostrand's Eclectic Engineering Magazine*, and published in a series of articles. It contains in general a description of the manufacture of wire cables, after the method invented and patented by the late John A. Roebling, and followed by him and his son, Col. W. A. Roebling, in the construction of the largest suspension bridges of this country. It also includes such theoretical investigations as pertain to an exact regulation of a cable, or chain, which may be found convenient in practice. The data of these calculations, as well as the diagrams of the apparatus and the description of the method of working, are taken from the East River Bridge, which,

by its magnitude and present erection, is a fit example. In view of the fact that the method of cable-making described is comparatively new and not generally known, and that great interest has been manifested by American and foreign engineers in the construction of the East River Bridge, and particularly of the cables, it is hoped, that the following pages, if they succeed in contributing something to the information of those interested in the subject, will not be unfavorably received.

W. HILDENBRAND.

New York, Sept. 1st, 1877.



# CABLE-MAKING

FOR

## SUSPENSION BRIDGES.

---

IN manufacturing wire cables, there are three different methods in use :

First, the cable is composed of twisted wire ropes.

Secondly, it consists of parallel wire strands, previously made on shore and then hoisted or hauled in position, or

Thirdly, it is made right in place; each wire is taken over separately and adjusted; and all of them are by a wrapping combined into a cable.

Each method has advantages, which in certain cases will recommend its application. A wire rope is easily handled and a cable of ropes can be formed quickly

and without the aid of machinery. In small or light bridges therefore, this kind of cable is found to be most advantageous. But the tensile strength of a straight wire is ten per cent. larger, than of one twisted; hence, in large bridges a rope cable in the first place would not be economical, requiring more material and costing more per pound than one formed of straight wires. Secondly, the bulk of the former will exceed the latter by forty per cent., offering therewith so much more surface to the wind and to the corroding action of the atmosphere. This is very important, and would in case of the East River Bridge, which is exposed to great gales and to salt water air, alone decide in favor of a cable of straight wires. Finally there is great difficulty in making good attachments of heavy wire ropes with the anchor chain, which at best will always be clumsy and require more extensive masonry than the compact and neat wire connection. A cable of wire ropes for the East River Bridge, consequently must be rejected.

Considering now the second method (which, for instance, was used at the Wheeling Bridge), we perceive, that it is only applicable, if in the line of the bridge behind either anchorage there is disposable room of the length of the cable. To manufacture the strands somewhere else and transport them in place is not possible, because a strand of straight wires can not be handled like a rope, and coiling it up would render it useless.

It is evident, that in the present case, where the bridge connects two crowded cities, such available room does not exist, and, therefore, that necessity already compels us to exclude this method. But even if the location would favor it, there are other reasons, which speak against strand-making on shore. When a number of wires, laid up straight without tension, are tied together and suspended in a curve, those in the lower part are considerably higher taxed than those in the upper. This difference of tension in the single wires may amount



to a loss of twenty-five per cent. in total strength. Through the elasticity of the material a certain equalization will take place, but nobody can tell to what extent, and the determination of tension in a single wire can only be hypothetical. Furthermore, it is no easy matter to handle a strand of fifty tons weight, which will exert a strain of forty tons, while being pulled over the towers and put in position. All points so far are decidedly in favor of the third plan. But one great disadvantage is connected with it, namely, the loss of time involved, from the fact that towers and anchorages must be finished, before cable making can commence. This is not the case with the first two methods; wire ropes or wire strands can be manufactured while the masonwork goes on, and after completion of the latter, they can be put in place at once. The advantages of making the cables in place are, however, as we have seen, so predominant, that there could be no hesitation in adopting this method at the East River

Bridge. It is hardly necessary to mention here the impossibility of moving the entire cable, finished, in its place, which opinion seems generally to prevail among non-professional people. Not to speak of the impracticability of its manufacture, the consideration—that it is 3577 feet long and weighs 870 tons, shows, that insurmountable obstacles would resist the locomotion of such a mass and that no tower could withstand the side thrust caused by the friction in taking the cable over.

Before going into details, I will premise by a description, in general outlines, of how the cables are made, using therein the dimensions and names of the East River Bridge. This will facilitate the understanding of the cable machinery and will also be applicable to any other suspension bridge by changing dimensions and names according to its size and location.

The floor of the East River Bridge, which is eighty-five feet wide, and destined to carry all kinds of traffic includ-

ing railway cars pulled by endless ropes, will be supported by four cables. These are suspended in three spans : a middle or river span of 1595.5 feet between centers of towers, and two side or land spans each 930 feet from center of tower to face of anchorage or  $954\frac{1}{2}$  feet to point of cable attachment. Each cable consists of nineteen strands of 332 parallel steel-wires and contains therefore altogether 6308 wires, which represent a total ultimate strength of 10,730 tons. Each strand is secured with a 7 inch pin of iron to two anchor bars  $1\frac{1}{2} \times 9$  inches. The wires do not pass around the pins directly, but around a cast iron shoe, which rests against the pin and which increases the curve of bending from 7 to 17 inches diameter. The last link of the anchor chain, to which the strands are attached, is arranged in four tiers. Each of the three lower ones is destined to hold five strands, the upper only four. While the strand is being made, it does not occupy the position it ultimately will have in the cable, but it

hangs at an elevation considerably above. This difference in height, which in our case amounts to 55 feet in the center of river span, is produced in two ways: first, on the towers the strand rests on rollers above the saddle and at the anchorages, the above-mentioned shoe is temporarily secured 10 or 12 feet behind the anchor pin to a casting called "the leg", which is specially designed for this purpose.

After the strand is finished, the shoes are relieved from their seats on the legs and let forward into their places on the anchor bars; at the same time the strand is lowered from the rollers on top of the saddle into the saddle, which double operation causes the vertex to sink in the correct position, previously determined upon by calculation.

There are various reasons for making the strand in a more elevated position. It is clear out of the way of the main cable; the latter does not interfere with regulation, which otherwise would be the case and which would delay the operation

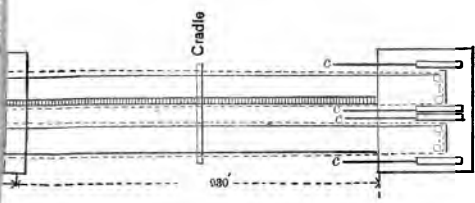
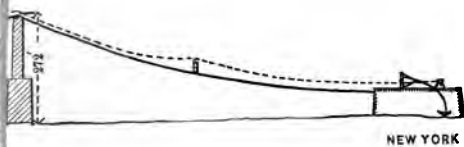
considerably. The flat curve, in which the wires are suspended, facilitates the tying together, and the separate attachment of the shoe gives ample working room for laying the wires into it. But the main advantage is derived from the fact that the tension in the wire is nearly doubled, amounting to about three quarters of the maximum tension to which it ever will be subjected in the finished bridge. This tests the wire to a certain extent, takes out all waves and bends, and leads to the easier detection of a defective wire or splice. It gives, therefore, to the engineer more or less assurance that all wires, worked in the cable, come up to the requirements and that the latter will obtain its calculated strength.

The running out of the wires takes place from the Brooklyn anchorage, where all wire rings are received. A number of them, spliced together, are wound on wooden drums, which are large enough to contain about 12—14 wires of the length of the whole cable. The end of a wire,

taken from the drum, is now temporarily fastened to the leg, and the loop, formed in this way, hung into a grooved wheel called "traveling sheave," which is firmly attached to an endless rope stretched from anchorage to anchorage. The latter, called "traveling or working rope," passes at each anchorage around horizontally placed wheels which, connected with a steam engine, give motion to it. The traveling sheave with two wires are carried over by the rope. One wire, which is fastened to the leg appears to stand still, while the other, which unwinds from the drum, runs with twice the speed of the working rope. After their arrival at the New York anchorage, the wires are taken from the sheave and laid around the shoe in such a manner, that all standing wires occupy one side of it, and all running wires the other. These two wires are now regulated according to a "guide-wire" which previously has been suspended and adjusted to the desired deflection. The same operation is repeated 166 times,

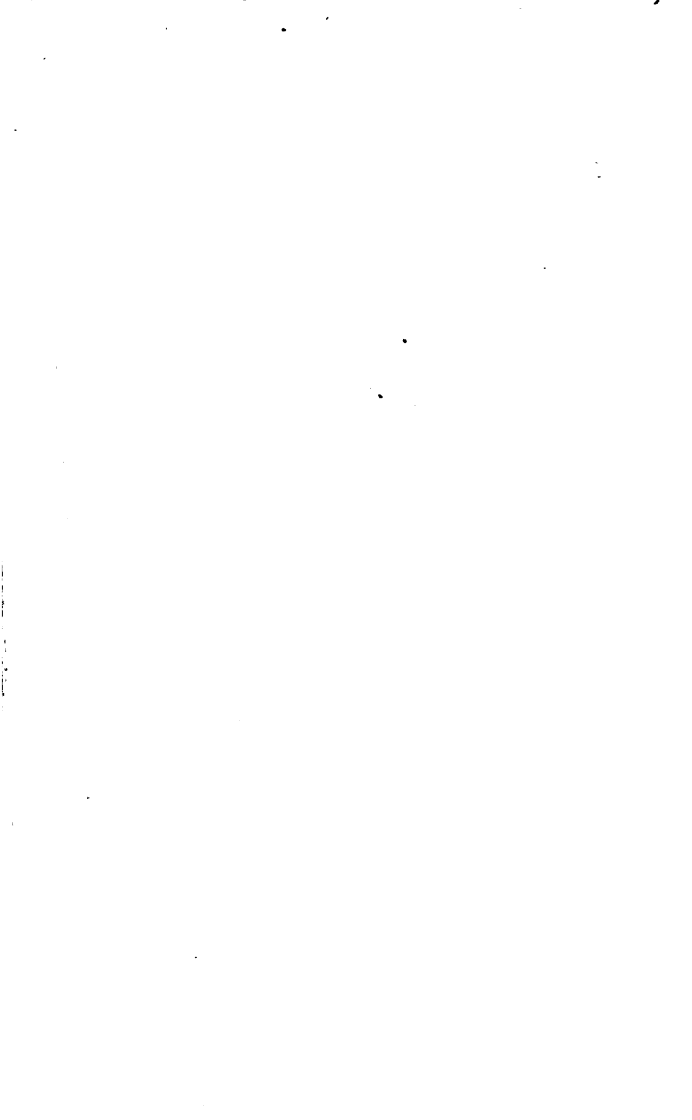
until all wires for one strand are stretched. The regulating is done by men standing on light platforms called "cradles," which, supported by wire ropes, are erected at different places along the line of the cable. It is therefore necessary, that these cradles should be at such an elevation, that the wires of the strand hang about breast high to a man standing in them, so as to enable him to compare the relative deflections of the wires.

In order to reach the cradles without difficulty and otherwise to facilitate general communication between all parts of the work, there is a narrow and light "footbridge," spanning the river and the spaces between towers and anchorages, which serves for all purposes. The wires of a strand are tied together with a wire lashing about every sixteen inches, and then lowered in their final position. A second strand is made in the same manner, and so on until with the nineteenth the cable is ready for wrapping. The strands occupy in the cable a certain



- fulldrawn lines, Cradle and foot bridge Ropes
- ..... dotted lines, Traveling Ropes
- final position of Cable in Centre span.





fixed order, and are regulated among themselves in shortening the longer ones by the insertion of an iron segment between shoe and anchor pin. All cables of the large suspension bridges, built so far, never contained more than seven strands; these of the East River Bridge are the first, which will be formed of nineteen strands. The number 7 or 19 is chosen for the reason, that the cable shall form a cylinder and a section through it shall reveal the strands in an order, that a circle can be drawn around them as tangent, (see Fig. 5.) Between 7 and 19 there is no number, which makes this possible.

After all the strands are regulated, the temporary lashings, which held the wires together, are removed, powerful screw squeezers press them in cylindrical shape, and a wrapping of No. 10 wire is put on, which finishes the cable. Figs. 1 and 2 show the position of cradle ropes, cradles and foot bridge, in elevation and ground plan; also the position of the wire-drums, anchor links, working rope

and a wire, while traveling across. The guide wires, or the strands in the high position, are only indicated in the ground plan in order not to confuse the drawing. In the elevation they would hang parallel to and a little above the cradle ropes.

The general description given above, shows us that for making a wire cable the following permanent and auxiliary structures, appliances and materials are necessary :

I. Anchorages for attachment and towers for support of the cables.

II. Auxiliary structures and appliances:

1. Means and machinery for taking wires over. Traveling rope, etc.
2. Certain places along the line of the cable, from where the wires can be adjusted. Cradles, etc.
3. Means of access to these cradles. Footbridge.
4. A preliminary, carefully adjusted wire to regulate the others by,-- guidewire.

### III. The cable wire and method of working it into a cable.

1. The material and its treatment.
2. Regulation of wires and strands.
3. The wrapping of the cable.

All under heads I and II must be completed before cable-making can begin. The work at the East River Bridge was commenced on Dec. 26, 1869, when ground was broken for building the caisson for the Brooklyn tower foundation.

In August of 1876, after various interruptions, towers and anchorages were completed, and the first rope (one of the traveling ropes) was taken across the river. During the previous winter all machinery pertaining to traveling ropes, etc., was erected on the Brooklyn anchorage. Building cradles and footbridge, suspending the guidewires and other preparations required three-quarters of a year longer, until on May 29th, 1877, the first wire for actual cable-making was stretched. It is estimated, that it

will require from 2 to  $2\frac{1}{2}$  years to complete the four cables.

### I. TOWERS AND ANCHORAGES.

The building of the lofty stone towers and the massive anchorwalls, works of unsurpassed magnitude, has already been extensively described in various reports and scientific journals, so that I can confine myself to the repetition of some principal dimensions, especially as far as they have bearing on cable-making.

The towers, containing 40,000 cubic yards of masonry each, are built throughout of granite, coming from over twenty different quarries of Maine. Their dimensions are at high water line 140 by 59 feet, and on top below the cornice 126 by 43 feet. The summit is 272 feet, and the saddles in which the cables rest, 267 feet  $6\frac{1}{2}$  inches above high water. The cast iron saddles, (see Figs. 39 and 40), weighing 12 tons each, rest on 43 iron rollers of  $3\frac{1}{2}$  inches diameter, which are moveable on a cast-

iron bed-plate,  $4\frac{1}{2}$  inches thick and weighing 11 tons. On the flanges of a saddle, six short stands are cast, serving as bearings for three rollers, in which the strand rests during its construction. The middle roller is placed 6 inches outside the center of saddle, the saddle 7 inches beyond center of plate, and the latter 12 inches outside the center of tower, all in direction towards the land

This was done as a precaution, to provide for the probable motion of the saddle towards the river, and to prevent the resultant of pressure from intersecting the tower base at foundation further outside its center than it naturally does owing to the difference of inclination of river and land cable. It will subsequently be shown that this motion does not exceed two inches.

The dimensions of the anchorages, built of limestone with granite corners, are at the foundation  $132 \times 119$  feet 4 inches, at groundline  $124 \times 111$  feet and at top  $117 \times 104$  feet. In front the given widths are 10 feet less. Two arches

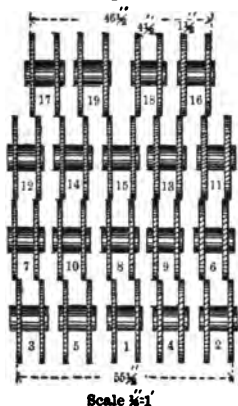
run lengthwise through the masonry, dividing it in three piers, in which the anchor chains are bedded. The total height of the anchorage above high water is at the face 89 feet from where it falls towards the rear with  $3\frac{1}{4}$  per cent.

The anchor chains consist of a double set of links, placed over each other. Each set contains ten links, arranged so, that the first two, starting from the anchorplate, are vertical, the next six form a quarter circle and the upper two are horizontal. In each link there are alternately 9 and 10 bars of sizes varying from  $3 \times 9$  inches for the upper to  $3 \times 7$  inches for the lower links. The pins also diminish proportionally from 7 to 5 inches in diameter.

Fig. 3 shows in side elevation the upper set of anchorlinks to which the strands are attached. The figures (Fig. 4) written between the bars indicate the order in which the strands are made in succession.

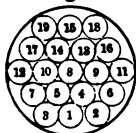
About 10 or 12 feet forward of the

Fig.4



shoe, the two halves of a strand are combined into one, and all strands, before leaving the masonry, are squeezed into a round cable, in which they occupy the following position : (see Fig. 5).

Fig.5

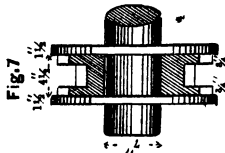
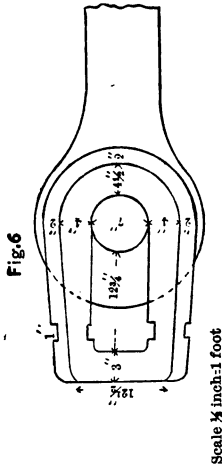


$\frac{1}{4}$ " = 1 foot



The cables as solid cylinders emerge from the anchorage eight feet below grade line of bridge.

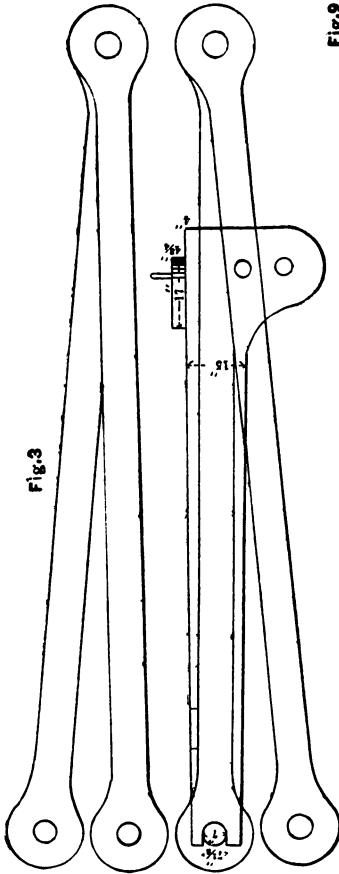
An important part in anchoring the strands is the "shoe" (see Figs. 6 and 7).



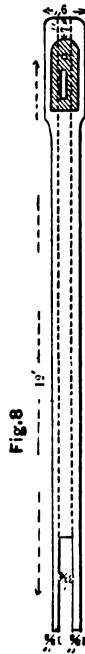
It should combine strength with the greatest compactness in order to reduce the width of the chain to a minimum. To resist the squeezing pressure of the strand the shoe is stiffened in front by a connecting piece; but enough length should be given to enable regulation of the strand. The advantages of the shoe are various. It increases the diameter of the curve around which the wires are bent, and it holds the latter between its flanges firmly, preventing any slipping after a wire is once regulated. In removing the strand from its temporary to its final position, the shoe especially is of great advantage, as all connections for hauling are made with the shoe, saving thereby the wires from injury or displacement.

The shoe in its first position rests on the so-called "leg," of which a description may be in place here, as part of the anchorage, though being only of temporary use :

The "leg" is a trough-shaped casting about 12 to 13 feet long. It is held in



Scale  $\frac{1}{8}$  Inch = 1 foot



front by the anchor pin and has in the rear a half round block cast to it for the shoe to rest against. Fig. 3 shows the side elevation of the leg in its position on the anchorbar, and Figs. 8 and 9 give ground plan and rear view. In order to prevent its rear end from rising through the tendency of the strand to draw upwards, a pin connects the two sides which straddle the bar.

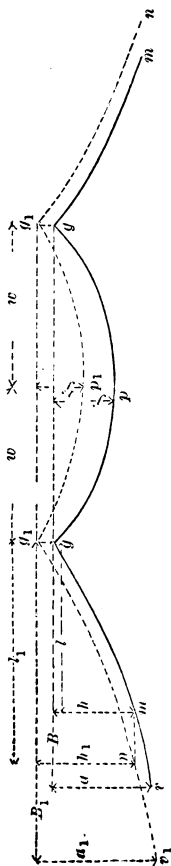
An important point in designing the leg is the determination of its length. This can be done best and surest by actual trial, in manipulating with the guidewire reversedly as afterwards with the strand. The guidewire is lifted from the saddle into the saddle rollers and both ends are pulled back until it has reached the elevation in which the strands shall be made. The distances for which the ends were pulled back give the length of legs. However, it is often desirable to have the legs cast before all other appliances are in readiness, in order not to delay the work. In such case this length must be determined by calculation.

The problem therefore is the following :

A wire, fastened at  $mm$  and supported at  $gg$ , is suspended with a deflection  $f$ . It is supposed that no friction exists at points  $g$ ; hence the three parts hang in perfect equilibrium, and the tension in the wire on both sides of  $g$  is the same. Now the supports  $g$  are raised to  $g_1$  and the points  $m$  moved horizontally to  $n$ , which causes the wire in Fig. 10 to take the position of the dotted curve with a fixed deflection  $f_1$ . The distance  $m n$  shall be determined. It will first be necessary to calculate the length of the whole wire in its first position, or, as the curve is symmetrical to the center line, half its length :  $\overline{mg} + \overline{gp}$ .

If the wire were to consist of perfect homogeneous material, it would hang in a catenary. This not being the case, we have a right to assume that the weight is equally distributed over the horizontal projection of the curve, or, in other words, that it forms a parabola. This assumption is the more justified by

Fig. 10



the consideration, that the future cable is uniformly loaded so heavily that the differences in own weight, calculated per foot of its horizontal projection, are vanishing.

Hence point  $m$  is a point of a parabola, which, if prolonged, would have its vertex in  $v$ . Taking point  $v$  as origin and calling the coordinates of  $g$  :  $a$  and  $B$ , those of  $m$  :  $(a-h)$  and  $(B-l)$ , we have as first condition :

$$\frac{B^2}{a} = \frac{(B-l)^2}{a-h} \quad (1)$$

The equality of the tensions on either side of  $g$ , gives the second condition :

$$\frac{\sqrt{B^2 + 4a^2}}{2a} Bq_1 = \frac{\sqrt{w^2 + 4f^2}}{2f} wq$$

$q$  and  $q_1$  signify the weight of the wire per unit of length in center and side span. The actual tension being of no importance, we assume  $q$  equal to 1 and  $q_1$ , in consequence of the steeper curve equal to 1.01.

$w$  = half of center span = 799.65 ft.

$f$  = deflection = 121 feet.

The right side of above equation therefore is equal to a constant  $T$ , and we can write :

$$\frac{\sqrt{B^2 + 4a^2}}{2a} Bq_1 = T \quad (2)$$

Through the solution of equations (1) and (2), we find the unknown distances  $a$  and  $B$ .

It follows :

$$a = \frac{B^2 h}{2Bl - l^2}$$

$$B = \frac{l^3}{2(l^2 + h^2)} + \sqrt{\frac{\frac{h^2 T^2}{q_1^2} - \frac{l^4}{4}}{l^2 + h^2} + \left(\frac{l^3}{2(l^2 + h^2)}\right)^2}$$

The values for  $l$ ,  $h$  and  $T$  in our case are :

$$l = 952.55, \quad h = 188.3 \quad T = 2760.8,$$

which, if introduced, give :

$$a = 188.48 \quad B = 983.3$$

With the position of the vertex  $v$ , established through  $a$  and  $B$ , we are



now able to express the length  $s$  of the curve  $mg + gp$  in a formula :

$$s = w \left\{ 1 + \frac{2}{3} \left( \frac{f}{w} \right)^2 - \frac{2}{5} \left( \frac{f}{w} \right)^4 \right\} \\ + B \left\{ 1 + \frac{2}{3} \left( \frac{a}{B} \right)^2 - \frac{2}{5} \left( \frac{a}{B} \right)^4 \right\} \\ - (B-l) \left\{ 1 + \frac{2}{3} \left( \frac{a-h}{B-l} \right)^2 - \frac{2}{5} \left( \frac{a-h}{B-l} \right)^4 \right\}^*$$

\* The above formula gives the length only approximately. The mathematically correct formula is the following :

$$s = \frac{p}{2} \left\{ \sqrt{\frac{2f}{p} \left( 1 + \frac{2f}{p} \right)} \right. \\ \left. + \log. \text{ nat.} \left( \sqrt{\frac{2f}{p}} + \sqrt{1 + \frac{2f}{p}} \right) \right\} \\ + \frac{p_1}{2} \left\{ \sqrt{\frac{2a}{p_1} \left( 1 + \frac{2a}{p_1} \right)} \right. \\ \left. + \log. \text{ nat.} \left( \sqrt{\frac{2a}{p_1}} + \sqrt{1 + \frac{2a}{p_1}} \right) \right\} \\ - \frac{p_1}{2} \left\{ \sqrt{\frac{2(a-h)}{p_1} \left( 1 + \frac{2(a-h)}{p_1} \right)} \right. \\ \left. + \log. \text{ nat.} \left( \sqrt{\frac{2(a-h)}{p_1}} + \sqrt{1 + \frac{2(a-h)}{p_1}} \right) \right\} \\ \text{in which } p = \frac{w^2}{2f} \quad p_1 = \frac{B^2}{2a} = \frac{(B-l)^2}{2(a-h)}$$

$a-h$  being very small, the last member simply can be called  $B-l$  without committing a great error. All the values introduced, we find

$$s=1787.74 \text{ feet.}$$

The wire in the upper portion forms the curve  $ng_1p_1$ , the length of which also is equal to  $s$  (neglecting thereby the elongation to which the wire is subjected under the greater tension), hence:

$$w \left\{ 1 + \frac{2}{3} \left( \frac{f_1}{w} \right)^2 - \frac{2}{5} \left( \frac{f_1}{w} \right)^4 \right\} + B_1 \left\{ 1 + \frac{2}{3} \left( \frac{a_1}{B_1} \right)^2 - \frac{2}{5} \left( \frac{a_1}{B_1} \right)^4 \right\} - (B_1 - l_1) = s \quad (3)$$

In this equation are three unknown values  $a_1$ ,  $B_1$  and  $l_1$ , consequently, to solve the problem, we need two other equations. They are found by expressing in symbols, that the tension of both curves must be alike, and that  $n$  is a point of the parabola  $v_1g_1$ :

---

For flat curves both formulas are almost identical. In our case the error is less than of a foot.

$$\frac{\sqrt{B_1^2 + 4a_1^2}}{2a_1} B_1 q_1 = \frac{\sqrt{w^2 + 4f_1^2}}{2f_1} wq = T_1 \quad (4)$$

$$\frac{B_1^2}{a_1} = \frac{(B_1 - l_1)^2}{a_1 - h_1} \quad (5)$$

In the last three equations is :

$f_1 = 66\text{ft.}$ ,  $h_1 = h + gg_1 = 190.42$   $T_1 = 4909.8$   
 $w$ ,  $q$  and  $q_1$  have the former values.

From the introduction of these values, follows :

$$B_1 = 1406.05, a_1 = 210.07 \quad l_1 = 964.65.$$

hence

$$\overline{mn} = l_1 - l = 964.65 - 952.55 = 12.1 \text{ feet,}$$

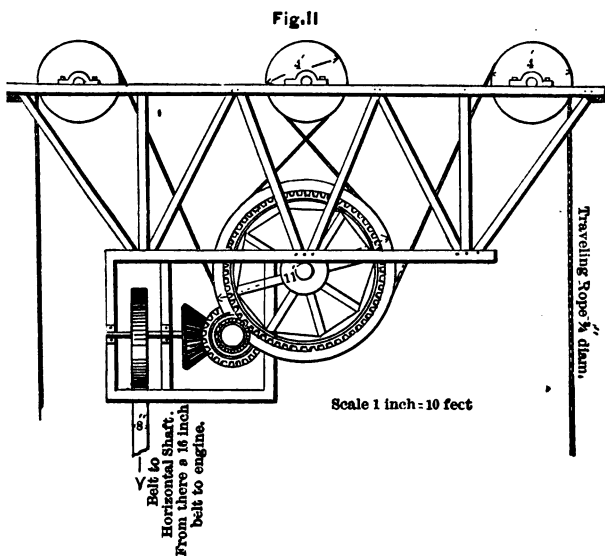
which represents the length of leg. Owing to a somewhat larger stretch, than was anticipated, in the cradle ropes, the above deflection of 66 feet was a little increased, in order to hang the strand most conveniently for the regulator.

This necessitated a shorter length of leg than calculated, which finally was fixed to 11 feet  $10\frac{3}{4}$  inches.

## II. AUXILIARY STRUCTURES AND APPLI- ANCES.

1. *Traveling rope.*—The “traveling or working rope” or “traveler” consists of a  $\frac{3}{4}$  inch steel wire rope, which forms an endless line around certain wheels placed on each anchorage.

Fig. 11 represents the arrangement on



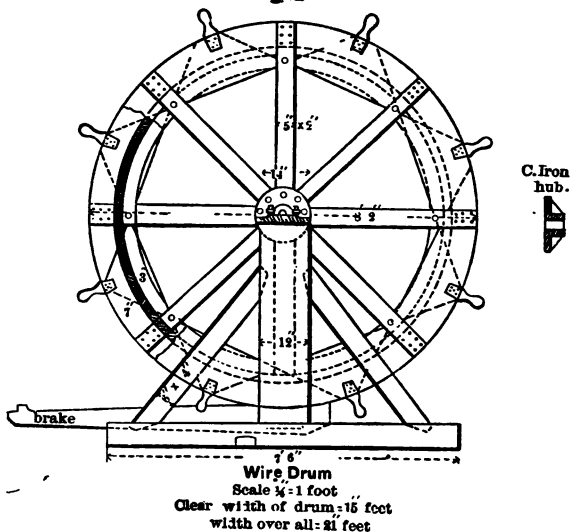
the Brooklyn side. The rope makes first two turns around a double grooved wheel 11 feet in diameter, called "driving wheel" and then passes around two smaller ones, called "guiding wheels," which keep the ropes in the desired distance from each other. On the New York side two similar wheels do the same service, which are fixed in a movable frame, so as to enable taking up slack in the rope. The driving wheel has a gearing on its circumference in which a pinion works of 15 inches diameter. On the pinion shaft is a mitre wheel in which are matched two others, both worked by a lever to throw them in or out of gear. The motion of the driving wheel and working rope can by these means be reversed. A 3 feet pulley on the shaft of these bevel wheels receives its motion by an 8 inch belt from another horizontal shaft which runs along the front face of the anchorage and which, by a 16 inch belt, is in connection with a steam engine located in the yard below. The 8 inch belt runs

loosely on the pulley and receives adhesion by tightening pulleys which enable the working rope to be set in motion or stopped, without stopping the engine. The engine has a 12 inch cylinder with 24 inches stroke, carries from 60—75 lbs. of steam and makes about 70 revolutions per minute. This corresponds to a speed of  $4\frac{2}{10}$  feet per second of the traveling rope, which therefore requires 14 minutes for a trip from anchorage to anchorage. The whole machinery, described above, is double; each set doing the work of carrying wire for two cables. The driving power is derived from the same steam engine. During its passage from anchorage to anchorage, the working rope is supported on the towers and on each cradle by properly placed sheaves. In close connection with the working rope is the "traveling sheave."

This is a light wooden wheel 5 feet in diameter with a grooved rim of zinc, in which the wire hangs, while traveling across. It is secured to the traveler by an iron, bent in the shape of a goose-

neck, so as to allow free passage of the rope over all supporting sheaves. An iron rod with a weight at the end, fastened to the hub of the wheel, keeps it in vertical position and prevents it being upset by the wind. Each working rope carries two traveling sheaves placed so, that one is at the New York anchorage,

Fig 12



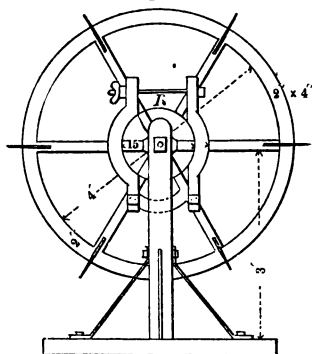


while the other is at the anchorage. When, for instance, the left sheave carries a wire from Brooklyn to New York, the right one moves empty in opposite direction. When the latter arrives at the Brooklyn anchorage, the driving wheel is stopped, a wire placed on the same, and the motion of the working rope is reversed.

Other appliances in the service of stretching wire are the wire drums. There are altogether 32 drums, 8 for each cable, the chief object of which is to serve as reservoirs of wire ready for being worked into strands. Each drum is 8' 2" in diameter, 15" wide and can hold about 50,000 feet wire, which is enough for six to seven trips of the traveling sheave. It is provided with a brake by means of which the sag in the running wire can be regulated. It is necessary that the wire is wound tight on the drum, else the brake is ineffective. The wire ring therefore is placed first on a smaller wheel (Fig. 13), from which it is unwound on the large drum under



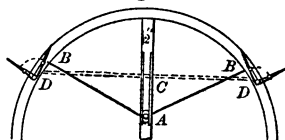
Fig.13



Scale 1 inch = 3 feet

considerable tension achieved by the brake *R* on the arms of the small drum. Small movable flanges (Fig. 14) admit

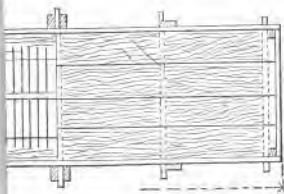
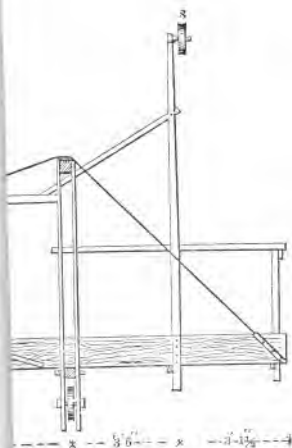
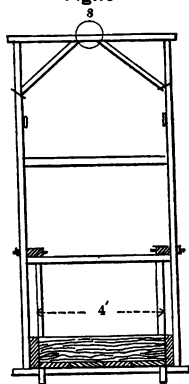
Fig.14

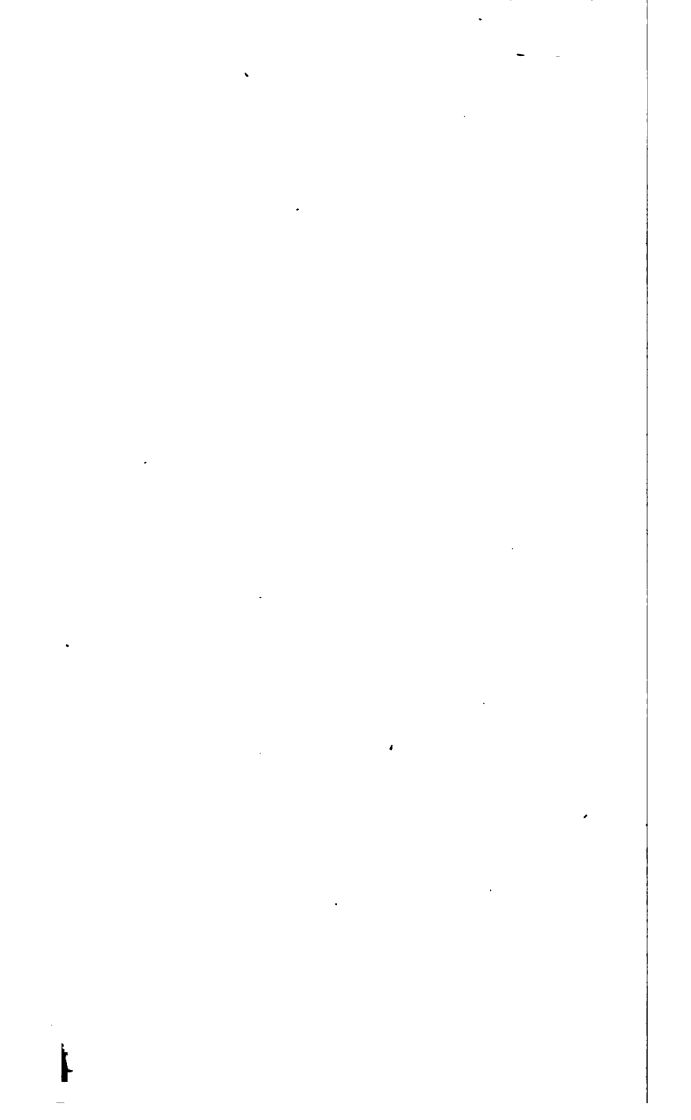


putting the wire on and hold it afterwards in place.

2. *Cradles and Cradle Ropes.*—The cradles are necessary for various

Fig.16





purposes. Their chief object is, as stated in the general description, to serve as platforms for men to stand on, who regulate the wires. They also are of value as intermediate supports of the traveling ropes and as a check for the lateral displacement of the wires by wind. Finally they serve as support to a few men, whose duty it is to throw the running wire on the other side of the strand.

There are altogether five double cradles, three in the river span and one in each land span. Owing to the fact, that the cables in the land span do not hang parallel to the axis of the bridge, but spread from anchorage towards tower, the single cradles have different lengths, those in the main span being 7 feet longer than the land cradles. On the opposite page one of the land cradles is illustrated in ground-plan, front and side elevation.

They are built throughout of oak and strengthened by light trussrods. The larger part of the platform consists of

an iron grating for the free passage of the wind, to which they are dangerously exposed in their lofty position.

The *cradle cables* which support the cradles, consist of  $2\frac{3}{8}$  inch crucible cast steel ropes with an ultimate strength of 180 tons each. One of the four ropes, which at the same time supports the footbridge is  $2\frac{5}{8}$  inches in diameter, and able to sustain 240 tons. The following is the weight on each cradle rope:

|                                       |             |
|---------------------------------------|-------------|
| Its own weight (9 lbs. per foot)..... | 14,580 lbs. |
| One half of three cradles.....        | 6,000 lbs.  |
| Working rope.....                     | 600 lbs.    |
| About 6 men.....                      | 960 lbs.    |
|                                       | <hr/>       |
|                                       | 22,140      |

It is suspended with a deflection of  $73'3''$  hence the largest tension in the rope is:

$$22140 \frac{\sqrt{800^2 \times 4 \times 73.25^2}}{4 \times 73.25} = 61000 \text{ lbs.} = 30\frac{1}{2}$$

tons. This gives a margin of safety of 5.8 times.

On top of towers the cradle ropes rest on wooden blocks, and at each anchorage they are attached to separate anchor bars

by means of wrought-iron sockets and screw stirrups, similar, only differently proportioned, to the connection shown in Fig. 21 and 22.

3. *The Footbridge.*—The footbridge has no direct service in cable making, but its indirect values are so great, that for the manufacture of large cables its erection may be deemed an absolute necessity. All the footbridges used by the late Mr. Roebling were built after the general plan of suspension bridges, namely, they consisted of a platform suspended from two cables. The writer of this, while working out the plans, suggested laying a platform directly on the cables, guided by the consideration, that a bridge parallel with the strand would enable the regulator to sight it at all points, that access to the cradles would be easy and that it would form a stiffer platform, which probably would suffer less under the violence of terrific gales, which rage almost weekly on the East River. Partially by these reasons, but especially for the accommo-

dation of shipping, the Chief Engineer adopted this plan, and it was executed accordingly.

The floor of the footbridge (Fig. 18) is formed of oak slats  $3'' \times 1\frac{1}{2}$  inches, 4 ft. long, set two inches apart, and nailed to two longitudinal strips of equal size. It is made in sections of twelve feet length and rests on the main footbridge ropes, to which it is secured with small screw stirrups (see Fig. 19).

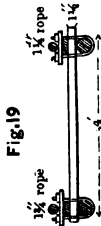
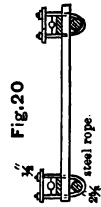
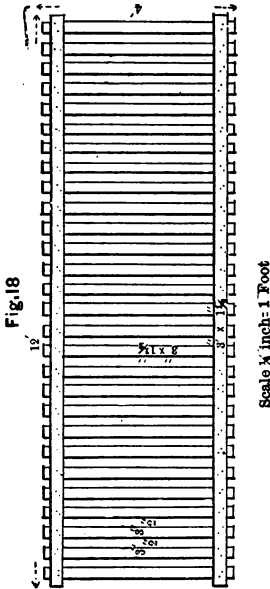
The main footbridge cables consist of  $2\frac{5}{8}''$  steel ropes, each having an ultimate strength of 240 tons. They are assisted by two auxiliary ropes of  $1\frac{3}{4}$  and  $1\frac{1}{4}$  inches in diameter; the heavier rope being on the side which also supports the cradles. The connection of these ropes with the floor is shown in Fig. 20.

The anchorage of the footbridge ropes is illustrated by Figs. 21 and 22.

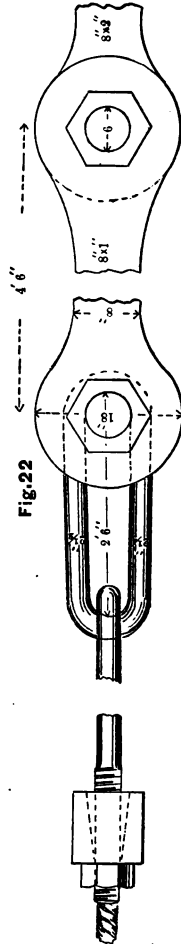
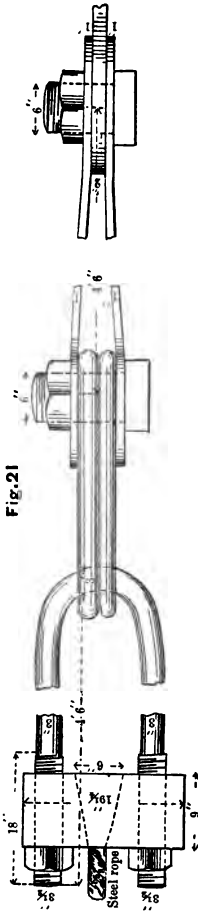
The socket for fastening the rope in, is made of the toughest wrought iron, contrary to the usual cast sockets of this kind. This precaution was taken to exclude any danger of bursting, which, in

a case like the present, would be followed by the greatest calamity (see Fig. 23).

The principal means for guarding the footbridge against gales, are two  $1\frac{1}{4}$  inch ropes which, fastened at the towers, are, in shape of inverted parabolas, suspend-

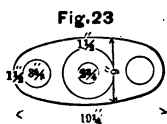






Scale  $\frac{1}{4}$  inch=1 foot

ed from the footbridge by inclined suspenders (see Fig 1). These "storm ropes" are assisted by a number of storm stays, which reach from the tower out as far as the first cradles. In the land-spans the storm guys are anchored in the ground. This whole system of guying has proved very successful, as even in heavy gales the motion of the bridge is confined to a small lateral displacement.



The maximum load coming on one footbridge cable is 62123 lbs. creating a tension of 86 tons. This is resisted by the aggregate strength of the  $2\frac{5}{8}$ " and  $1\frac{3}{4}$ " inch rope amounting to 318 tons; hence the margin of safety is 3.7 times.

All the ropes used for the footbridge, cradles, etc., were manufactured in the works of John A. Roebling's Sons, Trenton, N.J.

The footbridge ropes were first suspended with a deflection of 64.4 feet and sunk to 74.2 feet after the load was on (a foot more than anticipated). This amounts to a stretch of 2.26 feet in the whole rope, or to  $\frac{1}{111500}$  of the length, per square inch of section, per ton of strain.

The erection of all these structures was a difficult and perilous task, considering that the lowest point is 200 feet above the water, and that about 100 craft of all kinds cross the line of the bridge every hour.

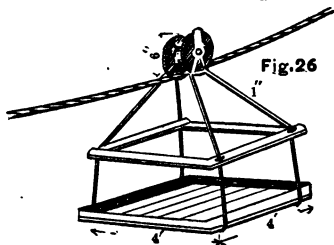
The first rope, taken over, was one of the travelers. Coiled on a reel, it was placed on a scow at the foot of the Brooklyn Tower. Its end was taken over the tower to the anchorage and temporarily fastened. Then the scow was towed across and the rope allowed to sink to the bottom of the river. The remaining part of the rope was taken from the reel and the end after passing over the tower, fastened to the drum of a steam engine. By observation it was

ascertained, that most every day an accidental coincidence of circumstances keeps for 6-7 minutes the line under the bridge clear of vessels. Of such a chance advantage was taken, and in the forenoon of Aug. 14th, 1876, a cannon shot gave the signal for cutting the lashing on the Brooklyn dock and setting the engine in motion. Four minutes later the rope came out of the water and in six minutes hung clear over all masts and formed the first connecting link between the cities of New York and Brooklyn, destined never more to be broken. Simple as this operation was, it created considerable excitement and interest among the population, probably caused by a feeling of historical importance for the day, which practically should unite the two cities. Thousands of spectators lined the shores, who greeted with loud cheers the appearance of this little rope, as it rapidly ascended high up in the air. It seemed that all doubts, hitherto entertained as to the erection and subsequent safety of the bridge,

had vanished from that moment. The East River Bridge was considered an established fact.

The other half of the traveling rope was taken over in the same manner and then the ends of both were taken to the New York anchorage and spliced together, making the rope endless.

In stretching the second traveller, use was made of the one already in position. The new rope was lashed to it and pulled over by the engine. Afterwards these lashings were cut away, which was performed by men running out on the traveler in a boatswain's chair or a "buggy." The latter (Fig. 26) consists of a platform four feet square, suspended by four iron rods to a grooved six inch roller, which runs on the rope.



An auxiliary, so called carrier rope, of  $1\frac{3}{4}$ " diameter was the next one stretched across. Its object was to carry the load of the footbridge and cradle ropes which were too heavy for the working rope. This carrier was hoisted up from out the water after the first method. The footbridge and cradle ropes were put in place in the following manner. Each rope was landed at the Brooklyn tower, its end hoisted up, passed around a sheave attached to the traveler, and lashed to a hemp rope which was connected with the drum of an engine at the New York anchorage.

As the rope moved on, it was supported by a "hanger" (see Figs. 24 and 25) every 50—60 feet, which consists of two hooks, for the rope to rest in, attached to a roller that runs on the carrier rope. These hangers were afterwards removed, leaving the rope suspended clear from the carrier.

After all ropes were in place, the cradles were hoisted on the towers and allowed to slide down to their proper

positions, in which they are secured by heavy lashings.

Fig.24

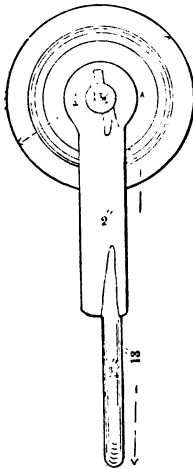
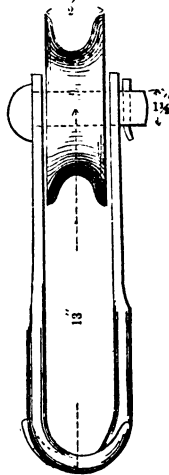


Fig.25



Scale  $\frac{1}{8}$  inch = 1 inch

Laying the footbridge floor was commenced simultaneously from both anchorages and the center of main span. It occupied but few days. Two light ropes, serving as handrails, lastly put in place, completed the footbridge, which since has been crossed by thousands of people.

4. *The Guidewire.*—The guidewire serves as a guide, parallel to which the single wires of a strand are suspended and adjusted. This is the work of a few minutes, while the regulation of the guidewire requires days and sometimes weeks; but once adjusted it guides all wires in the cable. With the commencement of every new strand it is lengthened an inch or two as a precautionary measure to assure sufficient lengths for the former. For too short a strand there is no remedy, while one longer than necessary is easily shortened in the manner already described.

The cable, which at first hangs parallel with the guidewire, occupies in the finished bridge a considerably lower position, caused by the weight of superstructure, etc. This last position must be determined before hand, and in the case of the East River Bridge depends upon the following considerations :

The law demands that the lowest point of the bridge in the center of the river shall in no case be less than 135



feet above mean high water. An indiscriminate raising of the cable however, would not only increase its tension, but also the grade of floor which already amounts to  $3\frac{1}{4}$  feet in 100'.

The latter difficulty might be overcome by lengthening the suspenders, but this again deprives the bridge of the advantage, obtained by short suspenders, viz., a rigid connection between cable and floor in the center of the span which prevents oscillations.

It follows, therefore, that a strict adherence to the maximum deflection is imperative. This deflection in the finished bridge will be 124.74 feet below saddle plates or 127.64 feet below the point of intersection of the two tangent lines, drawn common to cable and saddle in river and land span. Let us now examine the influences acting on the cable, which tend to change its elevation. They are of various kinds :

1. The weight of superstructure produces an elongation of the wires and hence a sinking of the curve throughout its length.

2. The diagonal stays, relieve the cable in the quarters next to the towers partially of its load, effecting a rise at these places and a depression of the central portion.

3. The inclination of the resultant of pressure towards the river causes a motion of saddles in the same direction, until equilibrium is established between the horizontal tensions of river and land cables. This will produce a further sinking of the cable in the middle span, and a rise in the side spans.

4. The cables are manufactured in a vertical plane, but afterwards they are drawn in an inclined position which causes the vertex of the center curve to rise again.

5. The changes in temperature cause the cable alternately to rise and fall.

Concerning the first point: *Elongation of Wires*.—Extensive tests have been made in regard to the stretch under a certain load. The modulus of elasticity averaged 29000000 which corresponds to an elongation of  $\frac{1}{14500}$  of its length per

net ton of strain per square inch of section :

2. *Effect of Stays*.—The usual method of calculating the strength of stays consists in attributing a certain equally distributed load to them, and in computing each single one according to the proportionate part of the load, and the angle which its direction forms with the stay. This of course gives only an approximate assurance that the stays really support all the weight allotted to them, and in consequence of this uncertainty some engineers have condemned altogether their application. They, however, neglect the consideration that the principal object of stays is not their supporting power, but the stiffness which they give to the floor. Except by such means, this same stiffness can only be attained by high and heavy trusses, which, though very effective, are considerably more expensive, besides adding greater weight and cost to the cables. For large bridges, therefore, stays are a matter of economy.

The following investigation will show what effect the stays, if supporting a certain load, have on the shape of the cable. Forcing the cable to take the calculated shape actually, will at the same time force the stays to support the assumed load; or reversedly from the shape of the cable the tension of each stay can be computed. Therefore the first objection to the application of stays becomes futile. But there exists a second and more serious one, namely, that in different temperatures they do not work in unison with the cable. This objection is justified in a great measure, and various devices have been proposed to overcome the difficulty. E. W. Serrell (see Report of Board of Consulting Engineers of New York and Long Island Bridge, Feb., 1877) proposes to suspend a lever from the saddles over the tower, and to attach the stays to a series of pivots placed on the line of this lever, so arranged that its movements compensate for the different contractions and expansions of chain and stays. Charles Bender

proposes to make suspender and stay in one piece, passing around a roller under the floorbeam. This arrangement is beyond doubt effective. Perhaps an advantageous modification of it might be, instead of making suspender and stay continuous, to attach them separately to a lever turning on a pivot, the arms of which could be so calculated as to confer on stay and suspender its due proportion of load.

The trusses of the East River Bridge are provided with expansion joints at the end of the stay systems, and the resultant motion of floorbeams compensates for elongations and contractions in stays and cable. This, however, is, in the present case, more a fortunate combination of circumstances than an inherent consequence of the arrangement. In all similar cases, it is therefore advisable to examine the movement of certain points of connection of suspender, stay and floorbeam, under different temperatures. The point being common to the three parts, its final position must be the

result of the motion of each single part. If not, the former equilibrium of forces is disturbed, and one or the other part is overstrained, or performs no work.

3. *Motion of Saddles*.—This takes place theoretically when the horizontal tension of the cable on one side of tower exceeds that on the other. But the friction of rollers counteracts this motion.

All formulas on rolling friction, as given in books, are based upon the supposition that it stands in direct proportion to radius of rollers and to the pressure. But this does not agree with actual experiments, on which alone a certain reliance can be placed. In general, our knowledge of rolling friction is small, and therefore, calculations based on it are more or less liable to errors.

W. Nordling (*Mémoire sur les Piles en Charpente Métallique des grand Viaducs*), experimenting with rollers of ten centimeters diameter, found the friction for a pressure of 1,000 kilo. to

be  $3\frac{1}{2}$  kilo. The result of a few experiments made by the author was 4.6 lbs. for 1,000 lbs. with 2 inch rollers and 5 lbs. with 1 inch rollers. Very thorough and valuable experiments were made by Shaler Smith on the friction of drawbridges, (see transactions of the American Society of Civil Engineers, August, 1874). He experimented with eleven different drawbridges, with each from 25 to 70 times, and found as average from six bridges with rollers of 2 feet 8 inches diameter, the friction to be 6.7 lbs. for 1,000 lbs. pressure, and 7.5 lbs. as average of five bridges with rollers of 1' 6" diameter. The rollers under the saddles of the East River Bridge are  $3\frac{1}{2}$  inches in diameter; the weight upon each saddle is about 1,250 tons. Comparing this case with Shaler Smith's experiments, and assuming that the friction will increase for smaller rollers in the ratio as he found, the friction will be  $9\frac{1}{2}$  to 10 lbs. per 1,000 lbs.

4. *Cradling of Cables*.—Changing the position of cables from a vertical to an

nclined plane will produce a negative factor in the causes for depression.

In other words, it will raise the vertex of outer cables 0.455 feet, and that of the inner 0.163 feet. Hence, the cables can be hung this much lower, and the above given deflection of 127.64 can be increased to 128.095 feet.

5. *Changes of Temperature.*—A difference of three degrees Fahrenheit causes the vertex of river cable to rise or to fall one inch. In the following calculation no reference will be taken of changes produced by heat and cold; it is sufficient to carry it out for a certain fixed temperature, and we assume the given deflection to take place at ninety degrees Fahrenheit. Afterwards the guidewire can be corrected according to the temperature of the day in which it is regulated.

The circumstance, that the motion of saddles is not known before hand, or in other words, that the relative span of middle and land cable is not defined, makes a general solution of the problem

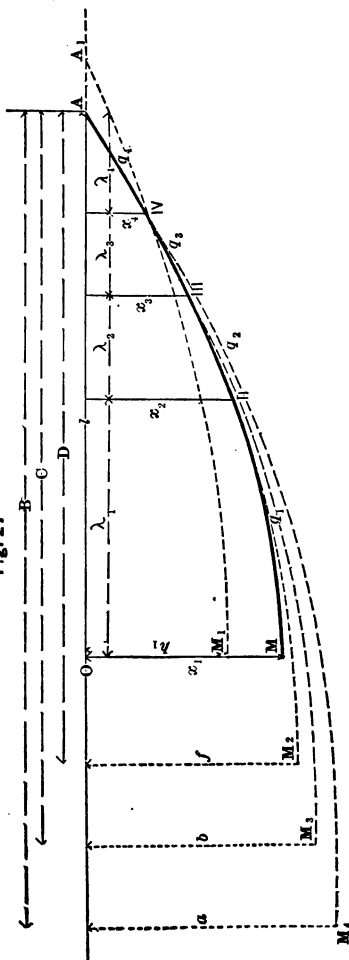


impossible. But under certain suppositions, the correctness of which afterwards must be proved, we can proceed in two ways. Either we guess the position of guidewire and see whether under all the different influences it will reach a final deflection of 128.095 feet—or else we assume the final position of saddles and work backward, calculating the rise of the cable which would take place if the superstructure were removed. The assumed position of saddles must afterwards be verified, which generally will require two or three trials and repetitions of the calculation. We proceed after the second method and consider therefore the following problem :

(See *Fig. 27.*)

Let  $AM$  be half the cable in its final position of the span  $2l$  and deflection  $x_1$ , loaded symmetrically per lineal foot with  $q_1$ ,  $q_2$ ,  $q_3$ , and  $q_4$  over the spaces  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , and  $\lambda_4$ . The load  $q_1$  represents the weight of superstructure per lineal foot;  $q_2$ ,  $q_3$ , and  $q_4$ , the same, less supporting power of stays within the spaces

Fig. 27



$\lambda, \lambda, \lambda$ . This supporting power is greatest near the tower and diminishes towards the outer stays on account of their greater length and smaller angle. For the sake of simplicity we assume only three variations and consider the load between two points equally distributed. Properly it changes from stay to stay, but the variation is so small that practically it produces no effect and would only make the formulas unnecessarily lengthy and inconvenient.

Under this supposition each piece between points I and II, II and III, etc., is part of a parabola which, if prolonged, will have its vertex in  $M, M_1, M_2$  and  $M_3$ , corresponding to the spans  $l, D, C$  and  $B$  and the deflections  $x, f, b$  and  $a$ . Calling the ordinates of points  $M, I, II, III$  and  $IV$  in regard to a horizontal line through  $A: x_1, x_2, x_3, x_4$  and the length of curve  $AM: S$ , we shall have to determine the following ten unknown parts:  $S, x_2, x_3, x_4, B, C, D, a, b, f$ , and need therefore ten equations. The whole system is a suspended polygon in equili-

brium, the single parts of it consisting of segments of parabola<sup>s</sup>. Expressing the length of the whole curve in the adopted symbols will give the first equation. Three more will be obtained in expressing the condition that points II, III and IV are points of certain parabolas. The horizontal force in each suspended polygon is equal throughout; this will give three other equations. Finally we receive three conditions in expressing that the tangents to points II, III and IV are each common to two parabolas. The length of curve  $AM$  is given in the following formula :

$$\begin{aligned}
 S = & B \left\{ 1 + \frac{2}{3} \left( \frac{a}{B} \right)^2 - \frac{2}{5} \left( \frac{a}{B} \right)^4 \right\} - (B - \lambda_1) \\
 & \left\{ 1 + \frac{2}{3} \left( \frac{a - x_1}{B - \lambda_1} \right)^2 - \frac{2}{5} \left( \frac{a - x_1}{B - \lambda_1} \right)^4 \right\} \\
 & + (C - \lambda_1) \left\{ 1 + \frac{2}{3} \left( \frac{b - x_1}{C - \lambda_1} \right)^2 - \frac{2}{5} \left( \frac{b - x_1}{C - \lambda_1} \right)^4 \right\} \\
 & - (C - \lambda_1 - \lambda_2) \left\{ 1 + \frac{2}{3} \left( \frac{b - x_2}{C - \lambda_1 - \lambda_2} \right)^2 \right. \\
 & \quad \left. - \frac{2}{5} \left( \frac{b - x_2}{C - \lambda_1 - \lambda_2} \right)^4 \right\}
 \end{aligned}$$

$$\begin{aligned}
& + (D - \lambda_4 - \lambda_3) \left\{ 1 + \frac{2}{3} \left( \frac{f - x_3}{D - \lambda_4 - \lambda_3} \right)^3 \right. \\
& \quad \left. - \frac{2}{5} \left( \frac{f - x_3}{D - \lambda_4 - \lambda_3} \right)^5 \right\} \\
& - (D - \lambda_4 - \lambda_3 - \lambda_2) \left\{ 1 + \frac{2}{3} \left( \frac{f - x_2}{D - \lambda_4 - \lambda_3 - \lambda_2} \right)^3 \right. \\
& \quad \left. - \frac{2}{5} \left( \frac{f - x_2}{D - \lambda_4 - \lambda_3 - \lambda_2} \right)^5 \right\} \\
& + \lambda_1 \left\{ 1 + \frac{2}{3} \left( \frac{x_1 - x_2}{\lambda_1} \right)^3 - \frac{2}{5} \left( \frac{x_1 - x_2}{\lambda_1} \right)^5 \right\} \quad (1)
\end{aligned}$$

Condition, that points *A* and *IV* are points of the same parabola:

$$\frac{B^2}{a} = \frac{(B - \lambda_4)^2}{a - x_4} \quad . \quad . \quad . \quad (2)$$

The same conditions for points *III* and *II*:

$$\frac{(C - \lambda_4)^2}{b - x_4} = \frac{(C - \lambda_4 - \lambda_3)^2}{b - x_3} \quad . \quad (3)$$

$$\frac{(D - \lambda_4 - \lambda_3)^2}{f - x_3} = \frac{(D - \lambda_4 - \lambda_3 - \lambda_2)^2}{f - x_2} \quad . \quad (4)$$

Equality of the horizontal force gives the following:

$$\frac{q_4 B^2}{2a} = \frac{q_3 (C - \lambda_4)^2}{2(b - x_4)} \quad . \quad . \quad . \quad (5)$$

$$\frac{q_4 B^2}{2a} = \frac{q_2 (D - \lambda_4 - \lambda_3)^2}{2(f - x_3)} \quad . \quad (6)$$

$$\frac{q_4 B^2}{2a} = \frac{q_1 \lambda_1^2}{2(x_1 - x_2)} \quad . \quad . \quad . \quad (7)$$

Tangent in point *II* is common to parabolas  $\overline{MII}$  and  $\overline{IIIII}$ :

$$\frac{\lambda_1}{x_1 - x_2} = \frac{D - \lambda_4 - \lambda_3 - \lambda_2}{f - x_2} \quad . \quad (8)$$

The same condition for points *III* and *IV*:

$$\frac{D - \lambda_4 - \lambda_3}{f - x_3} = \frac{C - \lambda_4 - \lambda_3}{b - x_3} \quad . \quad . \quad (9)$$

$$\frac{C - \lambda_4}{b - x_4} = \frac{B - \lambda_4}{a - x_4} \quad . \quad . \quad . \quad (10)$$

The solution of these ten equations seems at first laborious, but can be simplified much by introducing the following six new equations:

$$\left. \begin{aligned}
 \frac{(B-\lambda_1)^2}{B^2} &= n \\
 \frac{q_1}{q_4} \frac{\lambda_1^2}{B^2} &= m \\
 \frac{q_2}{q_4} \frac{(C-\lambda_1)^2}{B^2} &= p \\
 \frac{q_2}{q_4} \frac{(D-\lambda_1-\lambda_2)^2}{B^2} &= r \\
 \frac{(D-\lambda_1-\lambda_2-\lambda_3)^2}{(D-\lambda_1-\lambda_2)^2} &= s \\
 \frac{(C-\lambda_1-\lambda_2)^2}{(C-\lambda_1)^2} &= t
 \end{aligned} \right\} \quad (11)$$

From these follows:

$$\left. \begin{aligned}
 a-x_1 &= na & x_1-x_2 &= ma \\
 b-x_1 &= pa & f-x_2 &= ra \\
 f-x_2 &= rsa & b-x_3 &= tpa
 \end{aligned} \right\} \quad (12)$$

Substituting equations (12) in (1) the latter obtains the form:

$$\begin{aligned}
 \frac{a^2}{B} - \frac{3}{5} \frac{a^4}{B^3} &= \frac{n^2 a^2}{B-\lambda_1} + \frac{3}{5} \frac{n^4 a^4}{(B-\lambda_1)^3} + \frac{p^2 a^2}{C-\lambda_1} \\
 &- \frac{3}{5} \frac{p^4 a^4}{(C-\lambda_1)^3} - \frac{t^2 p^2 a^2}{(C-\lambda_1-\lambda_2)^3} \\
 &+ \frac{3}{5} \frac{r^2 a^2}{(D-\lambda_1-\lambda_2)^3} - \frac{3}{5} \frac{r^4 a^4}{(D-\lambda_1-\lambda_2)^3}
 \end{aligned}$$

$$\begin{aligned}
& -\frac{r^2 s^2 a^2}{(D-\lambda_4-\lambda_3-\lambda_2)} + \frac{3}{8} \frac{r^4 s^4 a^4}{(D-\lambda_4-\lambda_3-\lambda_2)^2} \\
& \quad + \frac{m^2 a^2}{\lambda_1} - \frac{3}{8} \frac{m^4 a^4}{\lambda_1^2} \\
& = \frac{3}{2} (S-l) \quad \dots \quad (1a)
\end{aligned}$$

Calling now:

$$\begin{aligned}
& \frac{3}{8} \left\{ -\frac{1}{B^2} + \frac{n^4}{(B-\lambda_4)^2} - \frac{p^4}{(C-\lambda_4)^2} \right. \\
& \quad = \frac{t^4 p^4}{(C-\lambda_4-\lambda_3)^2} - \frac{r^4}{(D-\lambda_4-\lambda_3)^2} \\
& \quad \left. + \frac{r^4 s^4}{(D-\lambda_4-\lambda_3-\lambda_2)^2} - \frac{m^4}{\lambda_1^2} \right\} = v \quad \dots \quad (13)
\end{aligned}$$

And:

$$\begin{aligned}
& \left\{ \frac{1}{B} - \frac{n^2}{B-\lambda_4} + \frac{p^2}{C-\lambda_4} - \frac{t^2 p^2}{(C-\lambda_4-\lambda_3)} \right. \\
& \quad + \frac{r^2}{(D-\lambda_4-\lambda_3)} - \frac{r^2 s^2}{(D-\lambda_4-\lambda_3-\lambda_2)} \\
& \quad \left. + \frac{m^2}{\lambda_1} \right\} = u \quad \dots \quad (14)
\end{aligned}$$

And substituting these values in (1a) we arrive at:

$$a^4 + a^2 \frac{u}{v} = \frac{3}{2} \frac{u}{v} (S-l) \quad \text{or:}$$

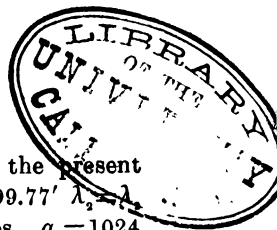


$$a = \sqrt{-\frac{u}{2v} \pm \sqrt{\frac{3}{2v}(S-l) + \left(\frac{u}{2v}\right)^2}} \quad (15)$$

A combination of equations (2), (3) to (10) results in:

$$\left. \begin{aligned} D &= \frac{q_1}{q_2} \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \\ C &= \frac{q_1}{q_3} \lambda_1 + \frac{q_2}{q_3} \lambda_2 + \lambda_3 + \lambda_4 \\ B &= \frac{q_1}{q_4} \lambda_1 + \frac{q_2}{q_4} \lambda_2 + \frac{q_3}{q_4} \lambda_3 + \lambda_4 \end{aligned} \right\} \quad (16)$$

If these values of  $D$ ,  $C$  and  $B$  are substituted in equations (11) we find  $n$ ,  $m$ ,  $p$ ,  $v$ ,  $s$  and  $t$ , and consequently we have in (12) six simple equations for determining the last six unknown parts. These are:  $b$ ,  $f$ ,  $x_2$ ,  $x_3$ ,  $x_4$  and  $a$  or  $x_1$ , according on which preliminary supposition the calculation was based. If originally the deflection of the guide wire was assumed, we know the length  $S$  and find  $(a)$  from equation (15) then (16) gives the unknown deflection  $x_1$ . If, on the other hand,  $x_1$  is known at the beginning, we find  $(a)$  from equation (16), and  $S$  by substituting its value in  $(1a)$ .



The numerical values in the present case are:  $l=799.55'$ ,  $\lambda_1=399.77'$ ,  $\lambda_2=\lambda_3=\lambda_4=133.26'$ ;  $q_1=1212$  lbs.  $q_2=1024$  lbs.  $q_3=762$  lbs.  $q_4=180$  lbs.  $x_1=128.095$ .

The span  $2l$  is equal to the distance between centers of towers plus the distances between these and points of intersection. By the trigonometrical survey the former was found to be 1595.5 feet, and two careful measurements made across the footbridge by two different methods gave for the same distance 1595.3 and 1595.4 feet proving the correctness of each result. In this calculation the figure of 1595.4 was taken as the mean value. The total load to be supported by stays will be 222500 lbs. divided so, that the first set between points *A* and *IV* supports 137500 lbs., the second 60,000 and the third 25,000 lbs. These weights deducted from the total weight and reduced to the lineal foot give the above values for  $q_1, q_2, q_3, q_4$ .

By substituting these values in equation (1) we find:

$$S=812.467'.$$

Now suppose all weight be removed, then the saddle will move from  $A$  to  $A_1$ , point  $M$  will rise to  $M_1$ , and the dotted curve  $A_1 M_1$  (see Fig. 27) will be the position of the guidewire. In order to find its deflection  $h_1$ , we must know the length of  $A_1 M_1$ . This is equal to  $AM$  less the contraction caused by removing from the cable all load, and consequently all tension.

At point  $A$  the tension is a maximum, expressed through:

$$q_1 \frac{B}{2a} \sqrt{B^2 + 4a^2} = 2892000 \text{ lbs.}$$

and at  $M$  a minimum:

$$\frac{q_1 \lambda_1^2}{2(x_1 - x_2)} = 2794080 \text{ lbs.}$$

The average between these two and the tension in points  $I$ ,  $II$ , and  $IV$ , is:

$$2849451 \text{ lbs.} = 1424.72 \text{ tons.}$$

If  $q_1$  was uniformly distributed over the whole cable, that is, if no stays would help in the support of the load, the deflection  $x_1$  would be 125 feet and

the maximum tension at  $A$  would be 3237858 lbs.

This compared with the greatest tension above reveals the curious fact, that, while the stays support  $\frac{2}{3}$ ths, of the total load, the tension in cable is decreased only  $\frac{2}{17}$ ths.

Calling  $L$  the length of cable  $A_1 M_1$ ,  $w$  its area in square inches,  $T$  the average tension, in tons, of cable  $AM$ , we find  $L$  by the formula:

$$L + \frac{L T}{14500 - w} = 812.467$$

$$T = 1424.72 \text{ tons } w = 133.928 \text{ } \square''$$

$$\text{hence } L = 811.871$$

If  $A_1 O$ , the span of guidewire, be called  $l_1$  we finally find its deflection  $h_1$ , through the relation:

$$l_1 \left\{ 1 + \frac{2}{3} \left( \frac{l_1}{h_1} \right)^2 - \frac{2}{3} \left( \frac{l_1}{h_1} \right)^4 \right\} = L$$

$$h_1 = \sqrt[3]{\frac{5}{8} l_1^2 \pm \sqrt{\frac{5}{2} l_1^4 \left( 1 - \frac{L}{l_1} \right) + \left( \frac{5}{8} l_1^2 \right)^2}}$$

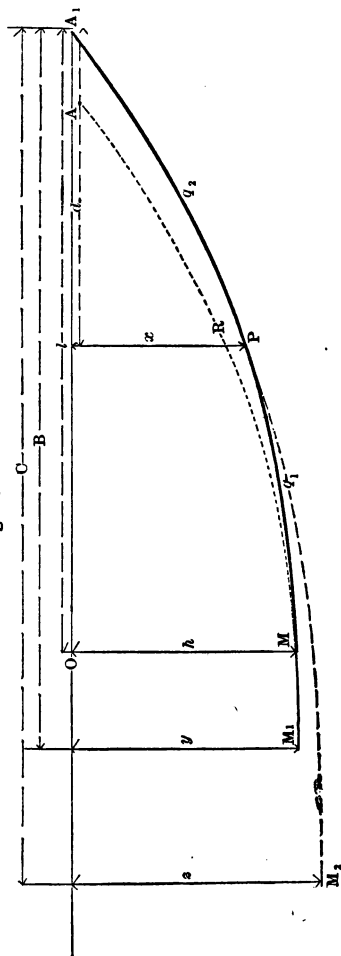
The distance  $AA_1$ , we supposed to be equal to 0.1 foot, hence

$$l_1 = 799.55 + 0.1 = 799.65 \text{ and } h_1 = 121.926,$$

which determines the deflection of the guidewire in case the assumption of the distance  $AA_1$ , will prove correct. This will be the case if with due regard to the friction of rollers, the horizontal tensions of river and land cables are alike. To determine the latter, a calculation similar to the one for middle cable, must be made; but it will be sufficient to consider the load supported by stays as equally distributed. Though this assumption will make a noted difference in the shape of curve, it will change the amount of horizontal tension so little as to be of no practical value, while on the other hand, it will much simplify the formulas. Considering the uncertainty in rolling friction, it is altogether not necessary to be too exact in this calculation.

In the diagram following, the curve  $ARM$  indicates the land cable, which was adjusted to balance the middle cable

Fig. 28



before being loaded. If now the weights  $q_1$  and  $q_2$  are suspended from it,  $A$  will move to  $A_1$  and the curve will take the position  $A_1 P M$ ,  $M$  being a fixed point. Our task is to find a relation between the abscissas and ordinates of the new curve, which will enable the determination of the horizontal tension. The average tension in curve  $A_1 P M$  must be equal to the average tension of middle cable, and as we know the length  $ARM$ , we also know the length  $A_1 P M$ . If  $M_1$  and  $M_2$  are the lowest points of the two parabolas  $MP$  and  $PA_1$ , the above length is also expressed by the equation:

$$S = C \left\{ 1 + \frac{2}{3} \left( \frac{z}{C} \right)^2 \right\} - (C - \lambda) \left\{ 1 + \frac{2}{3} \left( \frac{z - x}{C - \lambda} \right)^2 \right\} \\ + (B - \lambda) \left\{ 1 + \frac{2}{3} \left( \frac{y - x}{B - \lambda} \right)^2 \right\} - (B - l) \left\{ 1 + \frac{2}{3} \left( \frac{y - h}{B - l} \right)^2 \right\}$$

or:

$$\frac{z^2}{C} - \frac{(z-x)^2}{C-\lambda} + \frac{(y-x)^2}{B-\lambda} - \frac{(y-h)^2}{B-l} = \frac{3}{2}(S-l) \quad (1)$$

In this equation the higher powers of the fractions  $\frac{z}{C}$  etc., which are very small, were neglected, as greater accuracy is not necessary. The horizontal forces at  $A_1$  and  $P$  must be equal,

$$\frac{q_2 C^2}{z} = q_1 \frac{(B-\lambda)^2}{y-x} \quad . \quad . \quad (2)$$

In point  $P$  both parabolas  $MP$  and  $PA_1$  have a common tangent,

$$\frac{C-\lambda}{z-x} = \frac{B-\lambda}{y-x} \quad . \quad . \quad . \quad (3)$$

To these three equations must be added those of the two parabolas of which the whole curve is composed:

$$\frac{(B-\lambda)^2}{(B-l)^2} = \frac{y-x}{y-h} \quad . \quad . \quad . \quad (4)$$

$$\frac{C^2}{(C-\lambda)^2} = \frac{z}{z-x} \quad . \quad . \quad (5)$$

With these five equations we can determine the five unknown parts  $B$ ,  $C$ ,  $x$ ,  $y$  and  $z$ .



From (5) and (2) follows:

$$z-x = \frac{z}{C^2} (C-\lambda)^2 \quad . \quad . \quad (6)$$

$$y-x = \frac{q_1}{q_2} \frac{z}{C^2} (B-\lambda)^2 \quad . \quad . \quad (7)$$

and from a combination of (7) with (4):

$$y-h = \frac{q_1}{q_2} \frac{z}{C^2} (B-l)^2 \quad . \quad . \quad (8)$$

A result of these last equations is:

$$\left. \begin{aligned} B &= \frac{q_2}{q_1} (C-\lambda) + \lambda \\ y &= \frac{z}{C^2} (C-\lambda) (B-C) + z \\ x &= z - \frac{z}{C^2} (C-\lambda)^2 \end{aligned} \right\} \quad (9)$$

$$z = \frac{C^2 h}{2 l C - 2 l \lambda - \frac{q_1}{q_2} (l-\lambda)^2 + \lambda^2} \quad (10)$$

Substituting the values of  $z-x$ ,  $y-x$ ,  $y-h$  and  $B$  in equation (1) and calling  $\frac{3}{2} (s-l) = m$  we arrive after proper reductions, at:

$$\begin{aligned}
z^2 \left\{ 3 l C^2 + C \left[ (l-\lambda)^2 \left( 3 - 3 \frac{q_1}{q_2} \right) - 3 l^2 \right] \right. \\
+ \lambda^2 \left( 3 \frac{q_1}{q_2} - 2 \right) + \lambda^2 l \left( 3 - 6 \frac{q_1}{q_2} \right) + 3 \frac{q_1}{q_2} l^2 \lambda \\
\left. + \left( \frac{q_1}{q_2} \right)^2 (l-\lambda)^2 \right\} = m C^4 \quad . \quad . \quad (11)
\end{aligned}$$

Several expressions in (11) and (10) are constant, and we set, therefore, as an abbreviation :

$$\begin{aligned}
(l-\lambda) \left( 3 - 3 \frac{q_1}{q_2} \right) - 3 l^2 &= N \\
\lambda^2 \left( 3 \frac{q_1}{q_2} - 2 \right) + \lambda^2 l \left( 3 - 6 \frac{q_1}{q_2} \right) \\
+ 3 \frac{q_1}{q_2} l^2 \lambda + \left( \frac{q_1}{q_2} \right)^2 (l-\lambda)^2 &= R \\
2 l \lambda + \frac{q_1}{q_2} (l-\lambda)^2 - \lambda^2 &= p.
\end{aligned}$$

Substituting the value of  $z$  in (11), the latter obtains the form:

$$3 l C^2 + C N = \frac{m}{h^2} (4 l^2 C^2 - 4 l C p + p^2) - R$$

from which follows:

$$C = - \frac{N + \frac{4m}{h^2} lp}{6l - \frac{8m}{h^2} l^2} \pm \sqrt{\frac{\frac{m p^2}{h^2} - R}{3l - \frac{4m}{h^2} l^2} + \left\{ \frac{N + \frac{4m}{h^2} lp}{6l - \frac{8m}{h^2} l^2} \right\}^2}$$

The value of  $C$  once known it is easy by means of equations (9) and (10) to find  $B$ ,  $x$ ,  $y$  and  $z$ .

The numerical values of the constant parts are in our case:

$$l = 952.65', \quad h = 188.3'$$

$$q_1 = 1212 \text{ lbs. } q_2 = 748 \text{ lbs. } \lambda = 400'$$

which give the following results:

$$C = 1282.8 \quad z = 222.1,$$

hence horizontal tension:

$$H = q_2 \frac{C^2}{2z} = 2770592 \text{ lbs.}$$

This is 23488 lbs. less than the one in middle span; but the weight on one saddle is 1250 tons (the total superstructure weighing about 5,000 tons), therefore if

equilibrium exists between the two spans, the friction for 1,000 lbs. must be:

$$\frac{23488}{2500} = 9.4 \text{ lbs.}$$

This is the same as was found to correspond with the experiments, and, therefore, our supposition, that each saddle moves 0.1' towards the river, can be considered as correct and also the calculated deflection of guidewire.

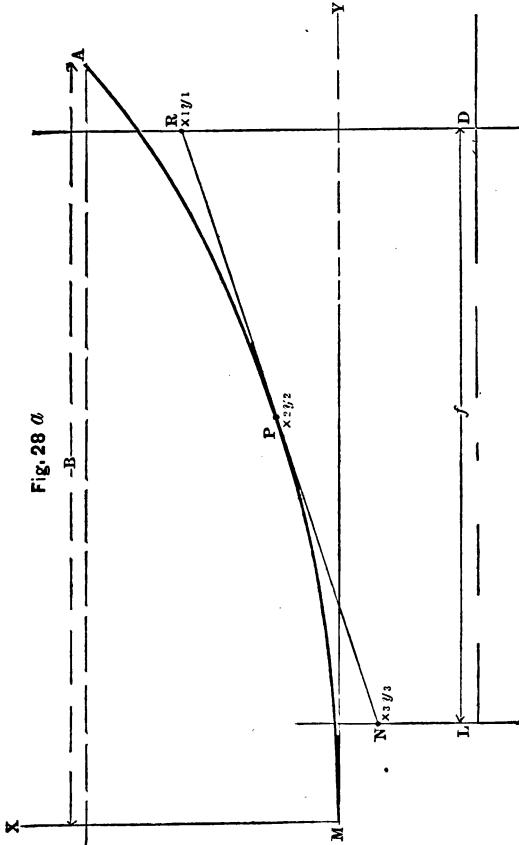
In regulating the guidewires for the East River Bridge, it was at first thought sufficient to adjust only the center span, and to rely upon the force of gravity to establish a balancing curve in each land span. But the result showed, that, though the wires were supported on small rollers, the friction was too great to allow a free rendering. A separate adjustment for each span was therefore deemed necessary.

Two guideboards placed on the same level were fastened across the archways in both towers and a level instrument, on a scaffold behind, was so adjusted,

that the cross line in the telescope coincided with the upper edges of both boards, while the telescope itself was level. With this arrangement it was possible to sight all four wires from the same position, because a turn of the telescope would not change the height of sight line.

The guideboards were moveable in an iron frame in order to adjust their height according to the temperature. A similar arrangement served for the land spans. A board was fastened to the masonry of each tower forty feet below saddleplate. A tangent line from the upper edge of this board drawn to the land curve, will intersect the face of anchorage at a certain height, which, determined by calculation, will serve to establish a sight line for the regulation.

*APM* (see Fig. 28a) represents the curve of land cable, *NR* the tangent in point *P*, *NL* the face of anchorage and *RD* that of tower. Taking *M* (the vertex of the curve) as origin of coordinates, *MY* as axis of ordinates and *MX* as axis



of abscissas and calling the coordinates of  $R, P$  and  $N : x_1, y_1, x_2, y_2$  and  $x_3, y_3$ , we have first the two linear equations :

$$y_1 = ax_1 + b$$

$$y_2 = ax_2 + b$$

from which follows :

$$y_1 - y_2 = a(x_1 - x_2) \quad (1)$$

$x_2, y_2$ , being also a point in the parabola, we have the relation :

$$y_2^2 = 2px_2 \quad (2)$$

and taking the differential of  $x_2$  :

$$2y_2 \frac{dy_2}{dx_2} = 2p$$

$$\frac{dy_2}{dx_2} = \frac{p}{y_2}$$

This is the equation for the tangent to point  $P$ ; but  $(a)$  also denotes this tangent in equation (1), hence we have  $a = \frac{p}{y_2}$  and (1) obtains the form :

$$y_1 - y_2 = \frac{p}{y_2}(x_1 - x_2)$$

$$y_1 = \frac{2px_2}{y_1} + \frac{p}{y_1}(x_1 - x_2)$$

The position of point  $R$  being a fixed one, its coordinates are equal to constants and we can set :

$$y_1 = c \quad x_1 = d$$

hence

$$y_2 = \frac{2px_2}{c} + \frac{p}{c}(d - x_2)$$

$$y_2^2 = \frac{p^2}{c^2}(d^2 + 2dx_2 + x_2^2)$$

or

$$2px_2 = \frac{p^2}{c^2}d^2 + \frac{p^2}{c^2}2dx_2 + \frac{p^2}{c^2}x_2^2$$

$$x_2 = \frac{c^2}{p} - d \pm \sqrt{-d^2 + \left(\frac{c^2}{p} - d\right)^2}$$

in which 
$$p = \frac{B^2}{2h}$$

$x_2$  being known, the value of  $y_2$  is found through equation (2) and  $x_3$  by the relation:  $y_1 - y_3 = a(x_1 - x_3)$  or as  $y_1 - y_3 = f$ :

$$x_3 = \frac{ad - f_1}{a}$$

A successful regulation can only be accomplished in perfectly calm weather, and it requires therefore careful watching for sometimes several weeks until a



favorable day offers itself. This was the case at the East River Bridge, where for three weeks all attempts of regulating were fruitless. As even a light breeze suffices to displace considerably a wire of such a length, and as the utmost exactness is imperative, the importance of an opportune day is evident. The wires used for guidewires were carefully selected from rings of equal weight per foot. It was necessary to examine about fifty rings in order to find three of equal weight. This shows the importance of the precaution. The regulating commenced on the New York land span and proceeded from there to middle, and, lastly, to the Brooklyn land span. Afterwards the wires were let free and found to be in perfect balance. In other less important cases, where a difference in deflection of a foot or eighteen inches is of no consequence, the calculation may be simplified by neglecting the higher powers of small fractions. Guessing, however, at the effects of stays according to existing bridges may be

simple and may apparently also result in a strong and substantial bridge, but, nevertheless, should not be recommended, because it deprives the engineer of the opportunity to calculate exactly the tensions in the different parts of his bridge, the ignorance of which may, if not fatal to the bridge, prove at least a loss of safety or of capital.

### III. THE MATERIAL AND THE MANNER OF WORKING IT INTO THE CABLE.

1. *The Cable Wire.*—In all bridge cables, constructed previous to those of the East River bridge, charcoal iron wire of either No. 10 or No. 9 gauge was used. The cables of the Niagara railway bridge, for instance, contain 3640 wires No. 10 gauge with an ultimate strength of 2658 tons, forming cables of 10 inches diameter. Those of the Cincinnati bridge—until now the largest suspension bridge ever built—are 12 inches in diameter and consist of 5200 No. 9 wires with an aggregate strength of 4212 tons. In comparing

with these the cables of the East River bridge, we find that the strength required for the latter exceeds over two and a half times the strength of the former cables. If composed of the same material, their bulk and the time required for making them would be increased in the same proportion, two items, which it is desirable to have reduced as much as possible. It was therefore concluded to manufacture these cables of steel-wire. In order to determine the size of the wire and the most advantageous quality of steel, very thorough experiments, continued over a series of years, were made with all kinds and grades of steel-wire of different sizes in regard to their tensile strength and ductility. As the result of these tests a wire was decided upon, as described in the following extract from the specification :

“The wire must be made of steel of superior quality, must be hardened and tempered and, lastly, must be galvanized.

The size of the wire shall be No. 8

full Birmingham guage. A length of 14 feet must weigh exactly one pound before it is galvanized.

“Each must have a breaking strength of no less than 3400 lbs. This corresponds in wire weighing 14 feet to the pound, to a rate of 160000 pounds per square inch of solid section. The elastic limit must be no less than  $\frac{47}{100}$  of the breaking strength, or 1600 pounds. Within this limit of elasticity it must stretch at a uniform rate, corresponding to a modulus of elasticity of not less than 27,000,000, nor exceeding 29,000,000 pounds.

“All wire must be ‘straight’ wire; that is to say, when a ring is unrolled upon the floor, the wire must lie perfectly straight and neutral, without tendency to spring back in the coiled form, as is usually the case. This straight condition must not be produced by the use of straightening machines, but by a patented process, which consists in leading the wire, from a point within the galvanizing trough, in a straight line un-

der considerable tension to the guide sheave or winding drum, and in locating the drum at such a distance as to permit the wire to be cooled and set before it is coiled thereon.

“There will be two kinds of tests :

“*First.* A piece 60 feet long, from every fortieth ring, is placed in a vertical testing machine which has a vernier guage, capable of being read to  $\frac{1}{10000}$

of one foot, so attached as to indicate the stretch of 50 feet of the wire. An initial strain of 400 pounds is now applied, which by successive increments of 400 pounds is increased to 1600 pounds. The amount of stretch for each of these increments shall be the same, and the total stretch between the initial and terminal strain shall not be less than

$\frac{97}{1000}$  of one foot equal to  $\frac{194}{100000}$  of the

50 feet. And furthermore, on reducing the strain to 1200 pounds, there shall be a permanent elongation not exceeding  $\frac{1}{100000}$  of its length.

"The minimum strength of the wire, if subjected to a breaking strain, shall be not less than 3400 pounds, and the minimum stretch, when broken, shall have been two per cent. in fifty feet, and the diameter of the wire at the point of fracture shall not exceed  $\frac{15}{100}$  of one inch.

"A piece 16 inches long, cut from every ring and a piece 6 feet long from one ring out of five, will be subjected to the same tests and must come up to the same standard.

"*Second.* Every ring will be subjected to a bending test, by cutting off from each ring a piece of wire one foot long and coiling it closely and continuously around a rod one-half inch in diameter, when, if it breaks, it will be rejected."

The contract, based on the above conditions, was awarded to J. Lloyd Haigh, of South Brooklyn, for  $8\frac{7}{10}$  cents per pound, with the distinct understanding that none but crucible cast steel shall be used for the wire.\*

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\* The wire furnished by the contractor exceeded con-

The wire is delivered in rings of 60-70 pounds, containing 800-1000 feet of the smaller, and 600-800 feet of the larger size.

Before being used, each ring receives three coats of oil, by dipping it first in a tank with raw, and then twice in one with boiled but cold linseed oil. Each coat of oil must be perfectly dry, before a new one is put on. After the oil has thoroughly hardened, the rings are ready to be spliced.

The splice used formerly for iron wire consisted in tapering the ends of the wires for about  $2\frac{1}{2}$ -3 inches, laying the flat sides upon each other and wrapping the whole with thin wire. By a blow on a specially prepared steel mould, the cir-

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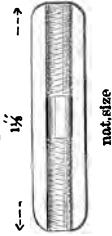
siderably the required ultimate strength, being in average 172,000 pounds per square inch. After two strands were completed with this wire, it was concluded to increase the size of the wire to 11 feet to the pound, equal to No. 7 Birmingham guage. This wire possesses a little smaller breaking strength, averaging about 170,000 pounds per square inch, but greater ductility. The principal advantage however, is, that instead of 332 wires, only 282 are necessary for one strand, which gives a saving in the time of manufacture of nearly one-sixth.

cumference of the wire received a number of small nicks or notches, which prevented the wrapping wire from slipping. This splice proved fully equal to the strength of No. 9 iron wire; but applied to heavy steel wire it averages, if well made, only a strength of about 24-2700 pounds, hence is insufficient for wire exceeding 3400 pounds. Experiments made with different kinds of splicing gave the preference to a screw-coupling, which by the smallest bulk had the greatest percentage of strength, and finally the splice, as illustrated in Fig. 29, was adopted for the East River bridge cables.

The screw threads at the end of the wires have this peculiarity, that the thread instead of being cut in the rod, is raised above it, so that between each turn there is a short straight piece of rod. This result is obtained by tapering the ends of the wires a little and turning a cylindrical screw on this cone. By a screw length of  $\frac{1}{2}$  inch for each wire, this coupling gives about 95 per cent. of the strength of the



Fig. 29



wire. After the ends of the wires are secured in the ferrule, the coupling is cleansed with a solution of potash, then dipped in molten zinc mixed with a little tin and finally painted with red lead.\*

2. *Strandmaking*.—After a number of wire rings are spliced together, the wire is wound on the wire drum, passing on its way through a piece of sheepskin saturated with oil. Every thing else pertaining to traveling rope, shoe and leg connection, etc., being prepared, we are ready to stretch the wires for the strand.

Figs. 30 and 31 show the rear part of the leg with the shoe and guide wire in position.

The end of the wire, with which the strand is started, is fastened to the side of the leg, passes around the shoe over the traveling sheave and back again to the drum. The lower wire, leading from

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\* To avoid the unscrewing of the wire from the ferrule during its passage across the river, which sometimes happened, the ferrule receives a little notch at each end, which being filled with zinc adhering to the wire, prevents its turning.

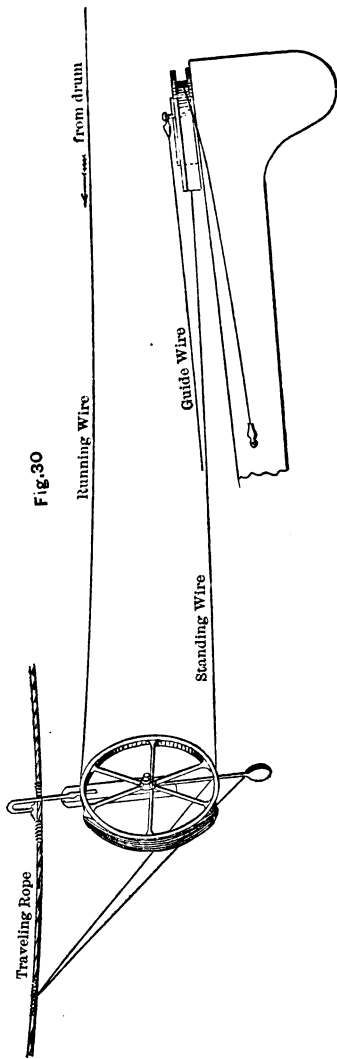


Fig. 30

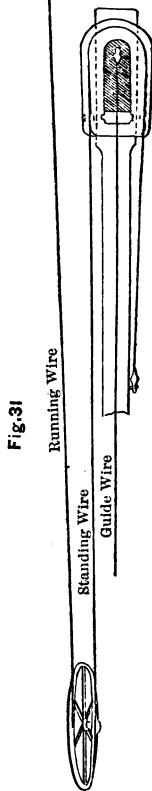
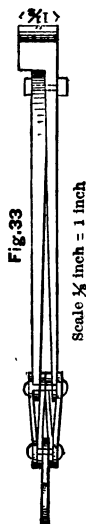
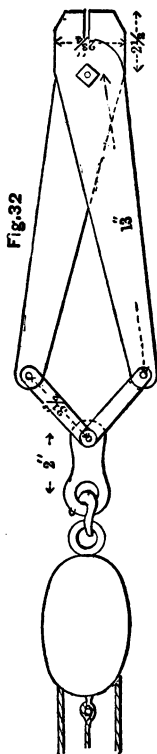


Fig. 31

shoe to traveling sheave, is called "standing wire," the upper, which uncoils from the drum and travels with twice the speed of the working rope, "running wire." In order to avoid confusion, it is necessary to preserve this distinction throughout the strand, and to keep each set always on the same side of the shoe. The standing wire occupies the inside, next to the traveling shoe, the running wire the outside of the sheave. The sag in the wires, while traveling across (see Fig. 1) is regulated by a brake on the wiredrum. As soon as the traveling sheave has passed the first tower, the standing wire is placed in the saddle and regulated in the first landspan. This is done by simply pulling it over the tower until it hangs parallel to the guidewire, and holding it in its place by a temporary twine lashing to some convenient object on or near the saddle. The running wire in the meantime travels on, supported by small wooden rollers outside of the saddle. After the traveling sheave has passed the second tower, the

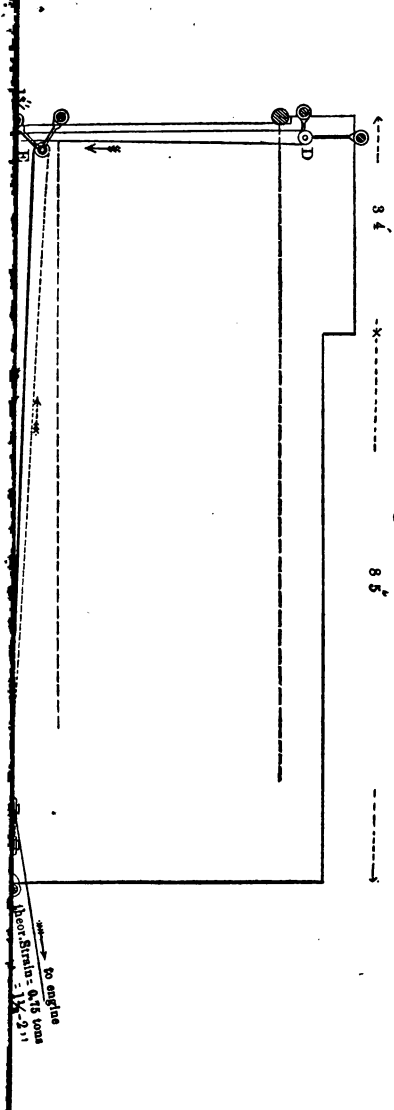
standing wire in middle span is immediately regulated in the foregoing manner, so that after its arrival at the second anchorage, only the last land span remains to be adjusted. This being done, the running wire is next thrown on the opposite side of the strand, and then regulated in the same way as the standing wire, but working in opposite directions. At the East River bridge the Brooklyn anchorage is the starting point; hence all standing wires are regulated from Brooklyn towards New York, and the running wires from New York towards Brooklyn. For adjusting the wires a pair of nippers as illustrated in Figs. 32 and 33 are used, and the hauling is done with a small block and fall fastened to some convenient place on the anchor-chain. While the regulation of these two wires is going on, the traveling sheave, which carried them over, returns empty and another sheave fastened to the opposite side of the working rope, brings two wires for the strand of the second cable.



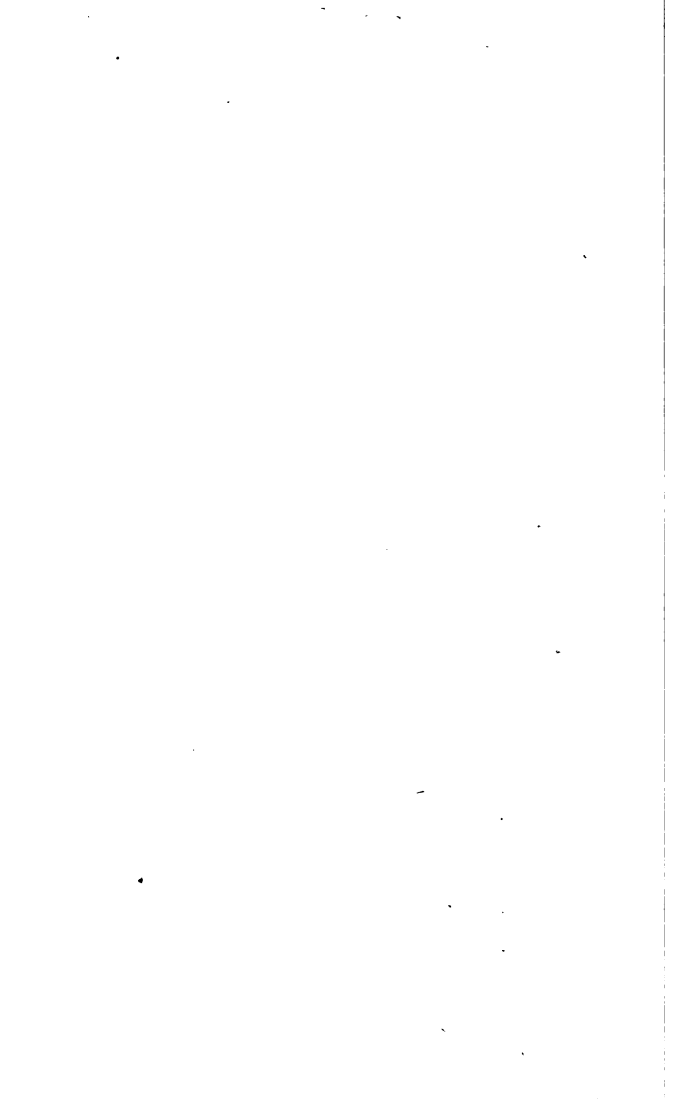
About nine or ten days are required to lay a strand of 280-300 wires, if no delays happen. After the last wire of the strand is in place, it is cut and spliced to the end of the first wire so that the whole strand is formed of one continuous wire. The latter operation is a delicate one, because the ends have to be cut so that the deflection and length come exactly right. A few trials with a temporary splice are therefore necessary to be made.

The next operation consists in tying the two parts of the strand together so as to form a round, solid little cable, which at the East River bridge has a diameter of  $3\frac{1}{2}$  inches. For this purpose a so called "carriage," as illustrated farther below in Figs. 43 and 44, is placed on the strand on top of the towers, in which a few men slowly descend towards the anchorages and center of river, tying during the passage the strand every 16-24 inches with four turns of No. 14 annealed galvanized wire. Before being tied, the wires are squeezed

Fig.34







together by means of a pair of tongs, on the claws of which an iron sleeve, by knocking it towards the end of the arms, exercises great squeezing power.

The strand is now ready to be "let off."

This consists in relieving the shoe from its temporary seat on the leg, and to let it forward in its final position, at the end of the anchor-chain. It is an operation, which, with heavy strands, requires great care and foresight, because an accident here would not only be a loss of many thousands of dollars, but also would cause immense damage to property and shipping, and likely great destruction of life. It is therefore advisable, not only to make careful calculations, but also to have every rope and iron used in this operation thoroughly tested.

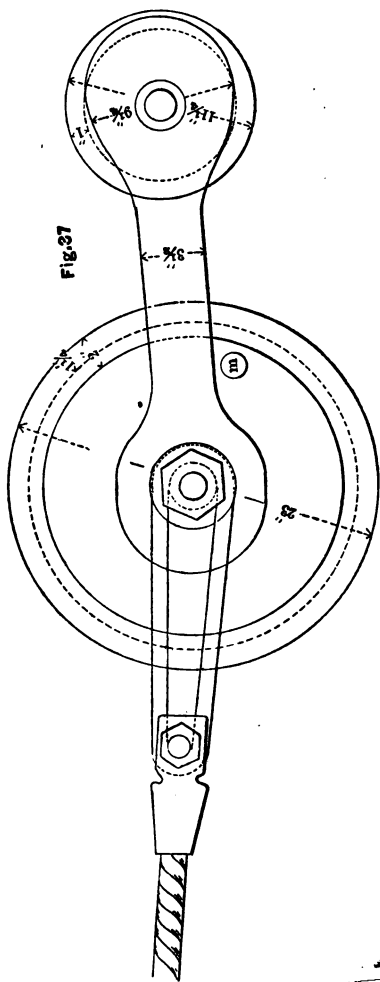
Fig. 34 represents the top view of the anchorage, with the full letting off arrangement for one of the outer strands of the East River Bridge.

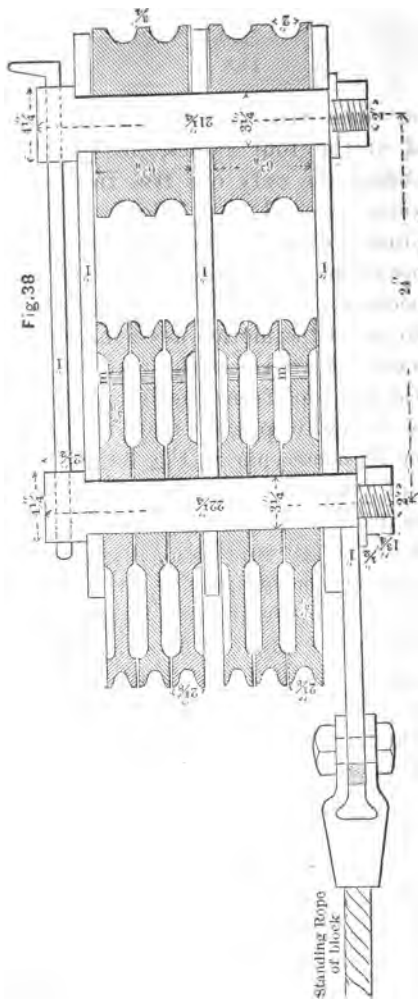
Two heavy iron bars *LL*, fitting closely to the sides of the shoe, and bolted to a double steel plate in front of it, form

the grasping arrangement. Figs. 35 and 36 show this on a larger scale.

At the end of the iron bars, are four 8 inch sheaves, which are attached by means of eight  $1\frac{5}{8}$  inch iron wire ropes to the four-grooved small sheave of a pair of blocks *B* and *A*. One of these is illustrated in Figs. 37 and 38.

Block *A* is the standing block, fastened stationary to a heavy log in the 'rear of the anchorage, by means of four  $1\frac{5}{8}$  in. wire ropes. It contains six iron sheaves of 23 in. diameter, connected to the sheaves of the running block *B* by means of a twelve folded  $1\frac{1}{4}$  in. steel rope, the fall of which after passing around several rollers *C*, *D* and *E*, is attached to a four sheaved wooden block *G* at the other end of the anchorage. This wooden block is worked by a  $1\frac{1}{2}$  in. manila rope, which connects with the drum of a steam engine. This arrangement of course, may be changed to suit different local requirements. In the present case, its advantages are: first, that the wooden block *G* moves only in the middle line





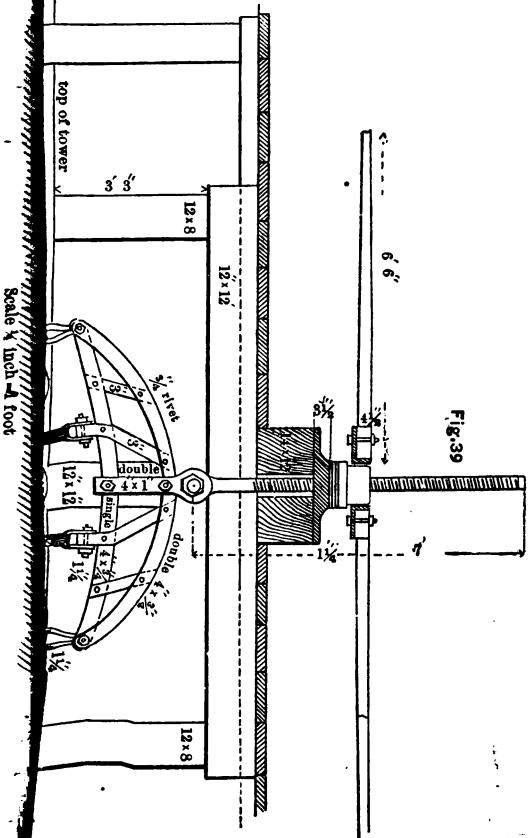
Scale 1 inch = 1 foot.

of the anchorage for letting off any strand of the four cables, this middle part being the only one free from obstructions; second, the length of the anchorage not being sufficient for moving the shoe in one process the entire distance, it is necessary to do it in two processes, viz., to arrest the motion as soon as the wooden block arrives at the rear end, to take the fall rope from the intermediate sheave *D*, and to place it from *C* directly over *E*, occupying in Fig. 34 the position of the dotted line. With this the double distance *D E*, is gained in the length of the fall rope, and the wooden block can be placed again so much back, to continue the operation. An arrest of the motion and a relieve of strain in the fall rope, can easily be procured, by lashing the twelve ropes, between standing and running block, tightly together. The tension in the strand is 75 tons, that of the fall rope, consequently  $7\frac{1}{2} = 6\frac{1}{4}$  tons + friction, equal together to about 8 tons, and that of the manila rope  $\frac{6\frac{1}{4}}{8} = \frac{3}{4}$  tons + friction, or about  $1\frac{1}{2}$  to

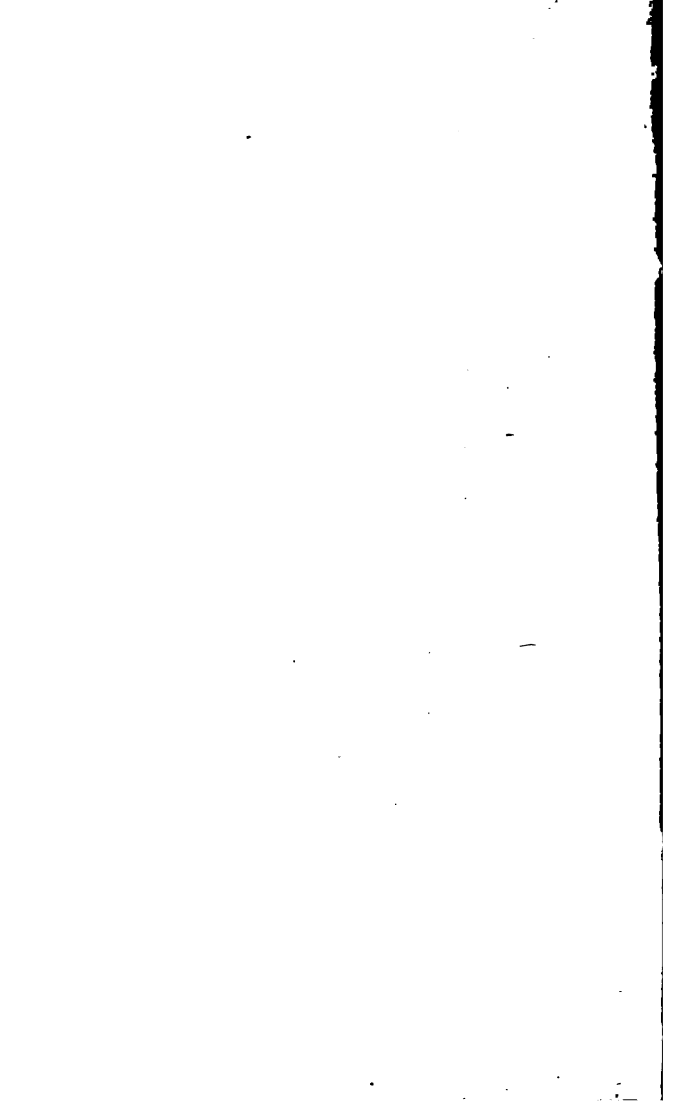
2 tons. The shoe must move 12 feet, hence the wooden block  $12 \times 12 = 144$  feet, and the manila rope  $144 \times 8 = 1152$  feet.

The operation commences in pulling the shoe  $\frac{1}{8}$  of an inch back from its seat on the leg, and to raise it above the latter in order to get it free. As the strand itself pulls upward, this rise of the shoe requires no extra force. The arrows in the diagram (Fig. 34) show the direction in which the different ropes move during the first operation. As soon as the shoe is free, and the motion of the engine reversed, it slowly travels forward until it reaches the eyes of the anchor links, through which a short pin is driven for the shoe to rest against. After having the shoe secured in this way, the tension in all the ropes is slackened, but the whole letting off apparatus is left intact, because it is needed again for regulating the strand.

*Lowering the Strand in the Saddle.*—This operation is illustrated in Figs. 39 and 40.



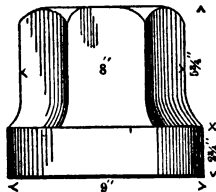




Two 14×12 inch timbers, supported on posts, resting on top of the masonry, bridge over the pit in which the saddles are placed. They give support to the nut of a  $3\frac{1}{2}$  inch screw of hammered iron, to the lower end of which a yoke-shaped iron frame is attached, which takes hold of the strand at different points, extending over a length of about six feet. The nut, shown on a larger scale in Fig. 41, is turned by means of a

Fig. 41

Nut.



cast iron spider (Fig. 42), which fits over the nut and which is provided with six open troughs for the insertion of wooden levers. As soon as the strand is lifted clear over the flange of the rollers, the latter, which rest in open bearings, are

taken away and the strand is slowly lowered in the saddle.

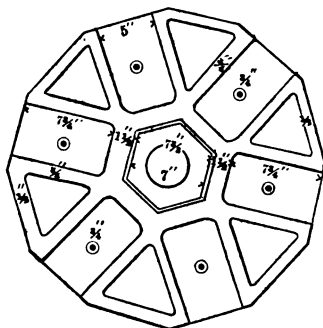


Fig.42

This operation finishes the work on the single strand, which is ready now to be regulated. The first strand of each cable theoretically needs no regulation, being parallel to the guidewire throughout. But practically there will always be some slight differences in their relative position, owing to inevitable small inaccuracies. It is, therefore, necessary to select the shortest as the guidestrand, and to adjust the others accordingly. The shortening is done in pulling the

shoe back from the pin, and inserting between the two an iron segment of the necessary thickness.

The strands of one cable, after being regulated, must occupy a relative position as shown in Fig. 5. In the middle span, where all strands hang parallel, there is no particular difficulty in doing this, but in the landspans, where the strands diverge from tower to anchorage, some special considerations are necessary for a successful execution. The leading idea must be, to adjust each single strand so that they all come just right if squeezed together and combined into a solid cable. As the land cable must form a balancing curve to the river cable, it is necessary that each strand shall do the same. Calculating, therefore, to each strand of the river span the equivalent curve of the landstrand, which passes through a certain fixed point, (the point where the cable leaves the anchorage), we are able to compute the length of the strand between this point and the point of intersection. To this length must be

added the distance from the face of the anchorage, to the point of attachment to the chain. These two together will give the total length of the landstrand, which will balance the corresponding riverstrand. Instead of measuring actually this length, to do which accurately would be impossible, we establish again tangent lines for the regulation, in the manner described for the guidewire. It is therefore necessary to find an equation between the coördinates of the curve and consequently the following problem must be solved: A parabola of a given length passes through to two fixed points, which have the horizontal distance  $B$  and vertical distance  $h$ ; the position of the vertex shall be determined. Calling the coördinates of this imaginary vertex in regard to the upper fixed point  $y$  and  $x$ , we have the following two equations:

$$y \left\{ 1 + \frac{2}{3} \left( \frac{x}{y} \right)^2 \right\} + (B - y) \left\{ 1 + \frac{2}{3} \left( \frac{x - h}{B - y} \right)^2 \right\} = S =$$

known length of curve, (1)

$$\frac{y^2}{x} = \frac{(B-y)^2}{x-h} \quad (2)$$

(equation of the parabola).

In (1) are the higher powers of the small fractions  $\frac{x}{y}$  and  $\frac{x-h}{B-y}$  neglected.

It follows from it:

$$\frac{x^2}{y} + \frac{(x-h)^2}{B-y} = (S-B)\frac{2}{3} = m$$

$$\text{or } x^2 B - 2xyh + h^2 y = mBy - my^2$$

from (2) follows:

$$x = \frac{hy^2}{2By - B^2}$$

The value of  $x$  substituted in the foregoing equation, we obtain:

$$\frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} + h^2 y = mBy - my^2$$

or:

$$\begin{aligned} \frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} + h^2 y &= mBy - my^2 \\ \frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} &+ h^2 y - mBy + my^2 = 0 \\ \frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} &+ h^2 y - mBy + my^2 = 0 \\ \frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} &+ h^2 y - mBy + my^2 = 0 \\ \frac{h^2 y^4 B}{(2By - B^2)^2} - \frac{2h^2 y^3}{2By - B^2} &+ h^2 y - mBy + my^2 = 0 \end{aligned}$$

The expressions in the brackets are constant, and we may call them  $a$ ,  $b$  and  $c$ , so that the equation will obtain the form:

$$y^3 + ay^2 + by + c = 0.$$

This is a simple equation of the third degree, which can be solved by introducing a new unknown quantity  $z$ , which is determined through the equation:

$$y = z - \frac{a}{3}$$

Calling for abbreviations:

$$b - \frac{a^2}{3} = u \text{ and } \frac{2}{27} a^3 - \frac{b}{3} a + c = v$$

and substituting all these values in the above equations it receives the following shape:

$$z^3 + uz + v = 0.$$

From this follows as one of the roots:

$$z = \sqrt[3]{-\frac{v}{2} + \sqrt{\frac{u^3}{27} + \frac{v^2}{4}}} + \sqrt[3]{-\frac{v}{2} - \sqrt{\frac{u^3}{27} + \frac{v^2}{4}}}$$

Calling the two parts of this expression  $k$  and  $n$ , the three roots of the equation are:

$$z_1 = k + n$$

$$z_2 = -\frac{k+n}{2} + \frac{k-n}{2} \sqrt{-3}$$

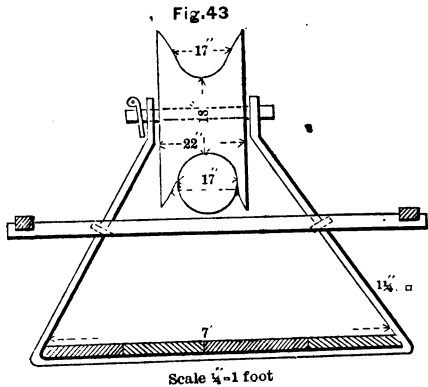
$$z_3 = -\frac{k+n}{2} - \frac{k-n}{2} \sqrt{-3}$$

If two of these roots should be found irrational, of course the rational one is the correct value of  $z$ . But if all three are rational, only that value is correct which satisfies equations (1) and (2). Having determined  $z$ , it is easy to find  $x$  and  $y$  or the equation of the curve, by means of which the tangent lines can be fixed. The actual calculation is very laborious as it contains large multiplications and figures in the 4th and 5th, power, but, on the other hand, the successful regulation of the strands is at stake, without which united action in the cable would not exist, or at least would be very uncertain.

3. *Wrapping the Cables.*—As soon as



the last strand is in position, the cable will be wrapped. The whole wrapping apparatus consists of three parts: the wrapping carriage (Figs. 43 and 44);

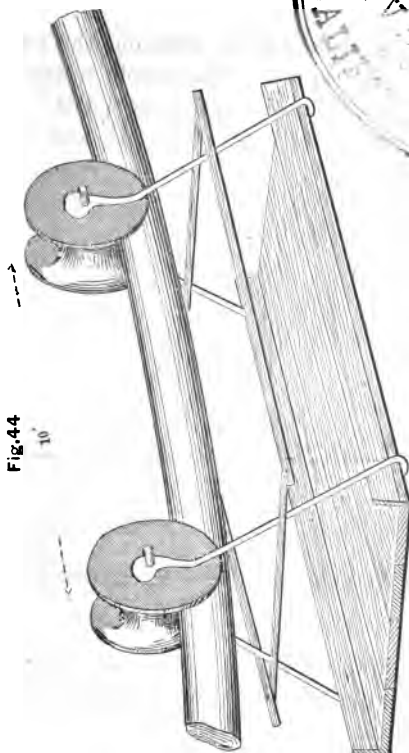


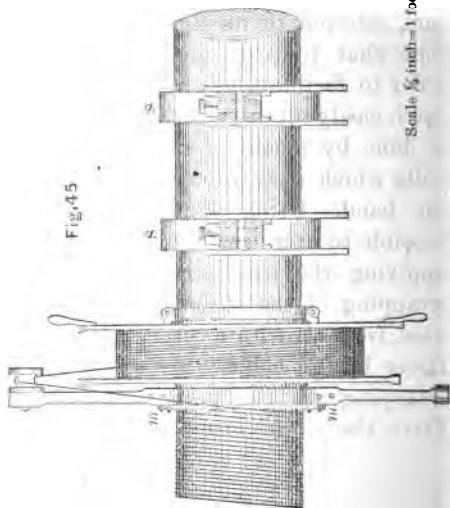
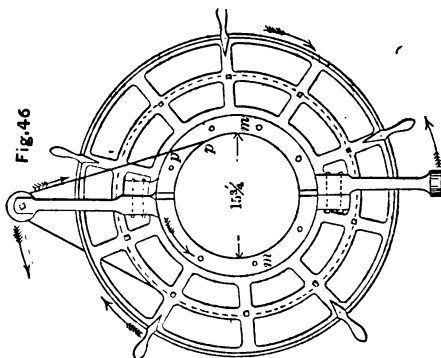
the squeezers (ss in Fig. 45) and the wrapping machine proper (Figs. 45 and 46).

A "carriage" is first placed on each cable at both sides of the towers. It is similar in construction to the one used



Fig. 44





for tying the strands, but having rollers wide enough to run on the cable. The object of this carriage is to serve as working platform for the men who handle the wrapping machine.

The squeezer consists of two half round steel-bands  $1\frac{1}{8}$  inch thick by  $3\frac{1}{2}$  inches wide, which fit on the cable or rather which, when placed on the loose strands, force the wires of the cable to assume a circular form. The upper part of the squeezer is provided with four ears, screwed to its side, which diverge somewhat towards their lower end in order to facilitate its slipping on and to catch easily all the wires. The squeezing is done by means of two 2 inch screw bolts which pass through the flanges of the band. Using long wrenches it is possible to exercise great power. Before applying the squeezers, the temporary wrapping of the strands is removed, at least from all within reach. At the East River bridge cables this squeezing and wrapping will be done in two processes. First the seven inside strands will be

treated like a separate cable, squeezed and wrapped, before the other strands are manufactured. Afterwards the operation will be repeated with larger squeezers and wrapping machines. In this manner the temporary wrappings of all the strands, save the middle one, can be cut and removed, which would not be possible if the loose strands of the whole cable had to be wrapped. Besides, this double process has the advantage of allowing tighter squeezing with less power, and altogether makes surer work. The cutting of the strand lashings is done a few feet in advance of the two squeezers, which are placed about 10 or 12 inches apart, the first one as near as possible to the saddle. Before tightening up the screws of the squeezers, the cable is once more saturated with oil, so that all the little spaces between the wires are completely filled and hermetically closed. The wrapping machine is now placed a short distance behind the first squeezer, and when the wrapping has reached the latter, this

squeezer is put 10 inches in advance of the second one, which in turn is placed the same distance ahead as soon as the wrapping has proceeded so far, etc.

The wrapping machine (Figs. 45 and 46) consists of a drum, formed of two light cast iron frames connected by wooden shrouding, which revolves on a cast iron barrel, that under considerable pressure can slide on the cable, but otherwise is immovable. On the same barrel, but independent from the drum, a ring  $\overline{mm}$  with a steel facing revolves, which has two arms, one having at the end a little roller, the other a weight. In the steel face of this ring, there is a small groove  $\overline{pp}$ , which runs in the line of the tangent from the circumference of the cable to the just mentioned roller. The whole apparatus is in two halves, which are screwed together after being placed on the cable. The wrapping wire, which is coiled on the drum, passes from here over the roller, through the groove, to the cable where its end is fastened. Now the drum is turned in

direction of the arrows and the two armed ring is turned in opposite direction. The first motion uncoils the wrapping wire, while the second winds it on the cable and at the same time keeps it by the momentum of the counter weight under great tension. As the wire passes through the groove in the steel ring, it squeezes itself, on account of the spiral lay, between the finished wrapping and the barrel and, consequently, pushes the latter ahead for a distance equal to the thickness of the wrapping wire. The ends of these wires are spliced, so that the whole wrapping in one span consists of one continuous wire. When the two wrapping machines meet in the center of the span, they are taken off and the two wires joined. Care must be taken, to wrap in opposite direction, so that the ends of the two last wires are on opposite sides of the cable and can be spliced under tension.

The wrapping wire generally consists of No. 11 or No. 10 annealed iron wire. For the East River bridge No. 10 galva-

nized wire will be used. Near the saddle, where the wrapping machine cannot be placed, the cable is bound together with iron bands about five inches apart. At the point in the anchorage, whence the different strands diverge, a heavy iron ring in addition must be placed, in order to lessen the strain on the wrapping wire. The single strands are wrapped by hand from this ring close to the shoe. Immediately after having wrapped the cable for a certain distance, it should be painted with several coats of good oil paint, so that the little spaces between the wires are completely filled up, giving to the cable a smooth cylindrical appearance and preventing the moisture to penetrate.

This operation finishes the cables, which are now ready to receive the superstructure. This should be put on symmetrically to the towers, and simultaneously in centre and land spans, in order to avoid uneven tension in the cable, and strain on the towers.

After the greater part is suspended,



the blocking, which held the saddles in place, is removed, giving to the cable free chance to move back or forth, and to assume its natural position of balance.

We have shown that under a certain temperature, this motion will be about two inches towards the river. The temperature under which the first strand of the East River bridge cable was regulated, happened to be 75—80° F. If the saddle blocking is removed on a colder day, the above motion will be less owing to the greater tension in the land cable, caused by greater contractions, than the river cable. The reverse will take place if the saddles are set free on a warmer day. Condition, however, always is that in each span the weight of the superstructure is the same, and symmetrical to the tower.

The lengths of the suspenders must be calculated according to the final curve of the cable, which is attained when the stays are put in place. Before this the floor will have an irregular shape, provided all suspenders have their exact

length. A continuous grade of the floor will, however, be established as soon as the stays are put under tension, which will cause the cable to assume that curve for which the suspenders were calculated, bringing thereby, the latter also under their proper tension.

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*Errata.*—Page 61, in Fig. 27, add to point *M* the denomination *I*.

Page 66, fifth line from above, instead of  $\lambda_2$ , read:  $\lambda_1$ .

Page 66, first line from below, instead of  $\frac{r^2 a^2}{D - \lambda_1 - \lambda_2}$  read:  $\frac{r^2 a^2}{D - \lambda_1 - \lambda_1}$ .

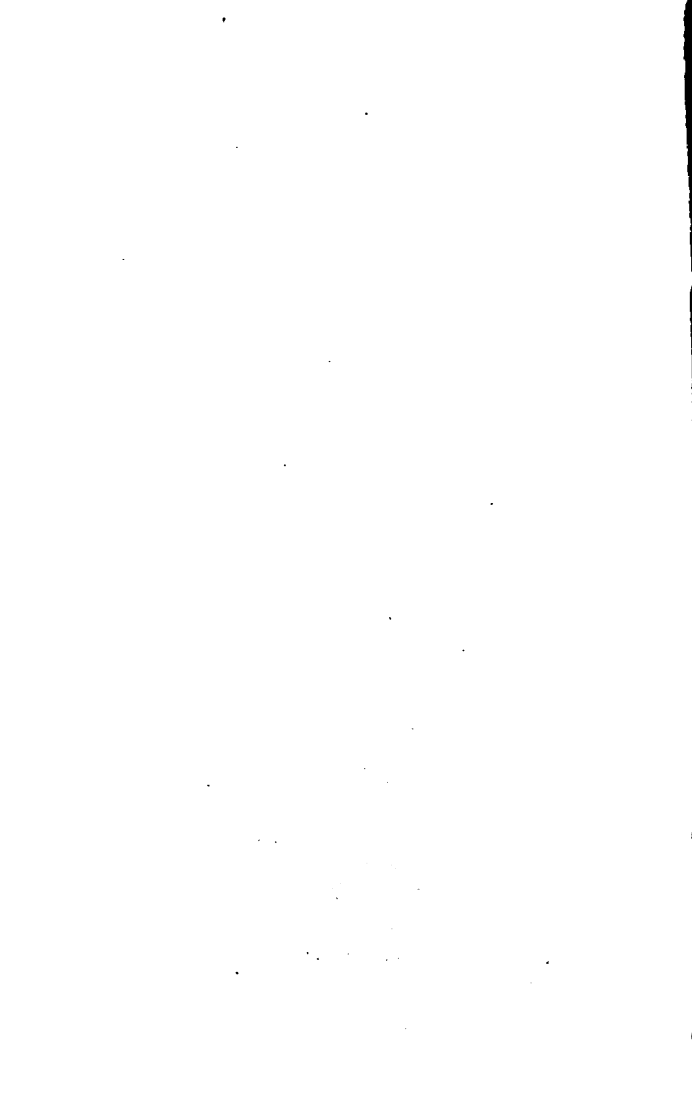
Page 66, second line from below, instead of  $-\frac{t^2 p^2 a^2}{(C - \lambda_1 - \lambda_2)^2}$ ,

read:  $-\frac{t^2 p^2 a^2}{C - \lambda_1 - \lambda_1} + \frac{2}{3} \frac{t^4 p^4 a^4}{(C - \lambda_1 - \lambda_1)^2}$ .

Page 67, sixth line from above, instead of =, read: +.

Page 70, sixth line from below, instead of *I*, *II*, read: *II*, *III*.

Page 71, twelfth line from above, instead of  $14500 - w$ , read:  $14500 \times w$ .



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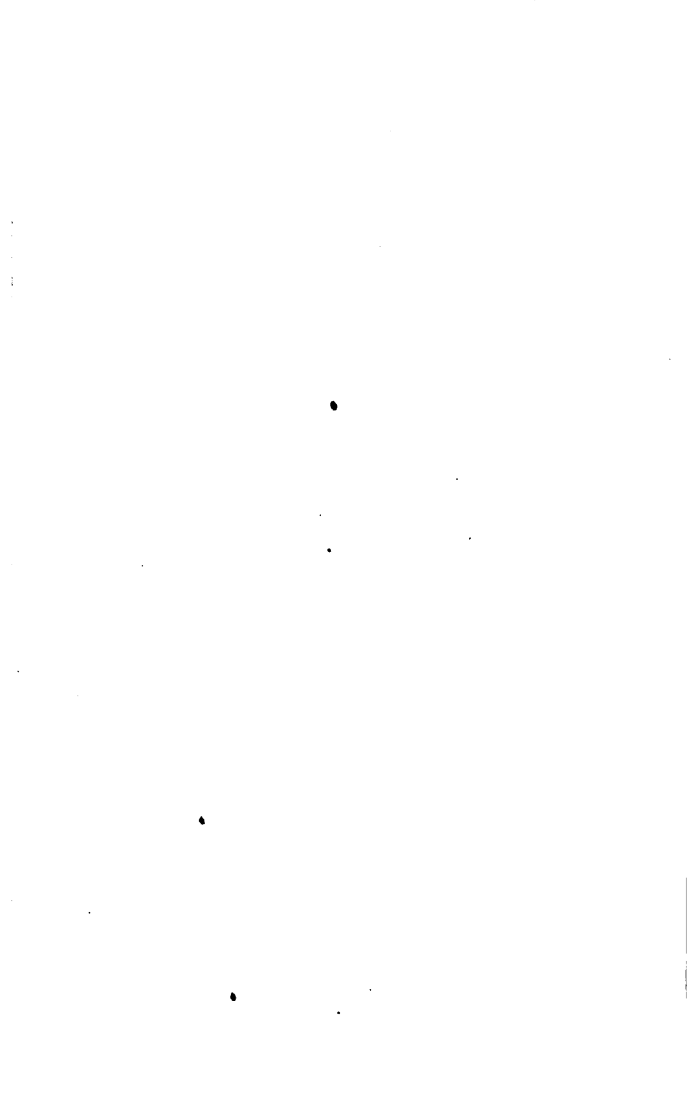
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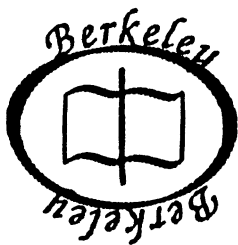
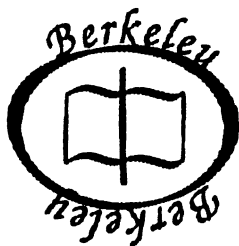
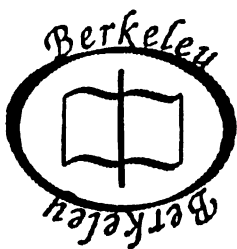
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